ATR-83-53-1

(1)

COWBOY TRAILS, PHASE I: SMALL-SCALE EXPLOSIVE TESTS IN SALT DOMES

PART I - GOALS, METHODS AND CONCLUSIONS

by
John G. Trulio
15 June 1983
Applied Theory, Inc.

PART II - EXPERIMENTAL PROGRAM

by
Franklin C. Ford
15 May 1980
Physics Applications, Inc.

Sponsored by
Defense Advanced Research Projects Agency (DoD)
DARPA Order No. 2694-A11
Under Contract No. DNA001-79-C-0376

Applied Theory, Inc.
930 South La Brea Avenue, Suite 2
Los Angeles, California 90036
(213) 857-5578

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: ATR-83-53-1
2. GOVT ACCESSION NO.: AD-A158 233
3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): Cowboy Trails, PhaseI: Small-Scale Explosive Tests in Salt Domes
5. TYPE OF REPORT & PERIOD COVERED: Final Report Jun 79 - Jun 80
6. PERFORMING ORG. REPORT NUMBER: ATR-83-53-1

7. AUTHOR(s): John G. Trulio, Franklin C. Ford
8. CONTRACT OR GRANT NUMBER(s): DNA001-79-C-0376

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Applied Theory, Inc., 930 South La Brea Avenue, Suite 2, Los Angeles, California 90036
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Program Code No. 9F1D, DARPA Order No. 2692, Program Element Code 62701E

11. CONTROLLING OFFICE NAME AND ADDRESS: Defense Advanced Research Projects Agency, Architect Building, 1400 Wilson Boulevard, Arlington, Virginia 22209
12. REPORT DATE: June 1983
13. NUMBER OF PAGES: 68

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office): Defense Nuclear Agency, Washington, D. C. 20305
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED (A)

DISTRIBUTION STATEMENT A
Approved for public release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Nitromethane, PETN, Pelletol, HNS, Salt, Cowboy Trails

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The energies of stock chemical explosives (CEs) most often vary with confinement. In Phase I of the Cowboy Trails program, CE spheres were therefore fired in dome salt, in mines near Hockley and Grand Saline, Texas. The Hockley charges weighed ~ 20-30 gm and those at Grand Saline ~ 75 gm. All were center-lit and buried deeply enough for containment. From the volumes of the resulting cavities and the known energy of one of the CEs (PETN), an energy, e, of 4.50 kilojoules (kj) per gram was found for nitromethane ("NM", another of the CEs). Constancy of the ratio of cavity-volume-increase, (ΔV), to the energy (E) released, which

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

theory and experiment both roughly aver, underlay the deduction of e_o. On that basis, values of e_o were also found for RDX, and for TNT at loading densities (ρ_o) of 1.59 and 1.21 gm/cc. For Pelletol, tamped as in Project Cowboy, e_o then becomes accessible via Cowboy-size bursts (Phase II); safety precludes the use of PETN at that scale, and NM takes its place. NM's e_o-value is now uncertain to the extent of $\sim$ 8%; the r.m.s. scatter of its measured values is $\sim$ 5%.

Cavities blown in the domes at Hockley (Phase I) and Winnfield, Louisiana (Cowboy) had the same ($\Delta V_c/E$)-value, within a margin of error ($\pm$8%) set by the uncertainty in e_o for Pelletol. Likewise, it appears that the change of dome and scale from Hockley to Grand Saline had no significant effect ($<$ 2%) on ΔV_c per unit mass of PETN, while ΔV_c increased by $\sim$ 8% per unit mass of NM. If so, then e_o varies with charge-size for the small masses of NM in Phase I, - but less effective containment of the Grand Saline charges than at Hockley clouds the issue. As for a change in dome alone, cavity volumes differ by only $\sim$ 4% between Winnfield and Grand Saline (Phase II).

Calculations of contained bursts in salt suggest that, for practical CEs, $\Delta V_c/E$ varies by $\pm$10% about a value of 1.16 cc/kj. Over that range, $\Delta V_c/E$ depends mainly on $P_J/\rho_o e_o$ ($P_J \equiv$ Chapman-Jouguet pressure). That parameter ($P_J/\rho_o e_o$) increases with the loading density of a given CE, and $\Delta V_c/E$ falls or rises depending on whether or not P_J exceeds a certain medium-dependent pressure P_α ($\sim$ 160 kilobars for dome salt). The physical explanation: As ρ_o (hence P_J) increases, the region of shear failure extends outward from shot-point to an ever-greater number of charge-radii. Still, the charge radius itself decreases and shock heating inhibits growth of the shear-failure region. With $P_J \ll P_\alpha$, shock heating is negligible and P_J increases so much faster than $\rho_o e_o$ that, for fixed E, the shear-failure region spans a growing radial distance (not just a growing number of charge-radii). Hence, ΔV_c increases with P_J until work done by the CE in shock heating rises so rapidly that the maximum radius of shear failure begins to fall ($P_J > P_\alpha$) - and with it ΔV_c.

Computing $\Delta V_c/E$ separately for NM and PETN causes our e_o-estimate for NM to drop to 3.83 kj/gm, which is too low; experimentally, e_o runs from 4.07 to 5.13 kj/gm, depending on confinement. The conflict needs to be resolved. It may stem from scale effects (e.g., NM masses too small for proper detonation), experimental error in Phase I, or errors in the material properties used to compute the ($\Delta V_c/E$) correction - sources of trouble whose respective effects on e_o can probably be learned by explosive tests in the laboratory, direct inspection of cavity-containing cores from the Hockley dome, and computations of spherical bursts with various models of CE and salt.

COWBOY TRAILS, PHASE I: SMALL-SCALE EXPLOSIVE TESTS IN SALT DOMES

PART I - GOALS, METHODS AND CONCLUSIONS

by

John G. Trulio

15 June 1983

Applied Theory, Inc.
930 South La Brea Avenue
Los Angeles, California 90036

PART II - EXPERIMENTAL PROGRAM

by

Franklin C. Ford

15 May 1980

Physics Applications, Inc.
2340 Harris Way
San Jose, California 95131

Sponsored by
Defense Advanced Research Projects Agency (DoD)
DARPA Order No. 2694-A11
Under Contract No. DNA001-79-C-0376

DARPA Order No. 2692

Program Code No. 9F1D

Program Element Code 62701E

Amount of Contract $40,464.00

Contract No. DNA001-79-C-0376

Principal Investigator and Phone No: Dr. John G. Trulio (213) 857-5578

Name of Contractor:

Applied Theory, Inc.

Project Scientist or Engineer and Phone No: Dr. John G. Trulio (213) 857-5578

Effective Date of Contract: 04 June 1979

Contract Expiration Date: 30 June 1980

Short Title of Work: Cavity Decoupling Studies

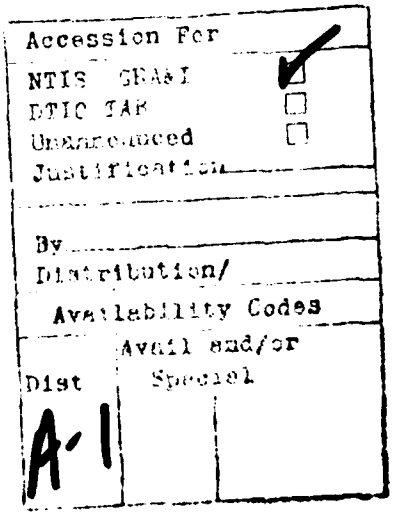


TABLE OF CONTENTS

PART I - GOALS, METHODS AND CONCLUSIONS

PART II - EXPERIMENTAL PROGRAM

COWBOY TRAILS, PHASE I: SMALL-SCALE EXPLOSIVE TESTS IN SALT DOMES
PART I - GOALS, METHODS AND CONCLUSIONS

by

John G. Trulio

SECTION 1
INTRODUCTION AND SUMMARY

In all likelihood, simple scaling rules apply accurately to dome salt.[1] That result, which opens a promising line of attack on nuclear monitoring problems, was deduced from Salmon and Cowboy data. However, those data are not complete enough to settle the scaling question; lab tests, which also favor simple scaling,[2] are not conclusive either. Moreover, on analyzing the data, we found that the problem of seismic-source definition runs deeper than had been thought, and in some unexpected directions.

Of particular concern is the finding that, even for peak radial stresses below a bar, salt does not deform elastically.[1] Since computational models have generally been inconsistent with that result[3] (at least until it was pointed out), there is scant reason to trust their predictions as to where nonlinear behavior ceases; indeed, they differ greatly among themselves on that critical point. Thus, even for deep shots that produce nearly spherical motions, explosions create seismic sources that are poorly known at present, and which can only be defined reliably by experiment.

As for other data-gaps: Comparisons between Salmon and Cowboy are muddied by the simultaneous changes in dome, overburden, and type of explosive, that they present. Also,

despite the contrary assumption almost always made in analyzing ground motion, the tamped Cowboy charges were not spherical. Then too (surprisingly) TNT charges release energy in amounts that vary by a factor of at least 1.9 with their conditions of confinement - and in all the Cowboy events, motion was driven by TNT in pellet form ("Pelletol"). The energy released by tamped Pelletol spheres and cylinders, center-detonated, is uncertain even now by at least 5%.

1.1 Phase I: Objectives and Approach

A series of salt-dome shots has just been completed to close these gaps in data. The main goals of Phase I of the program are to determine the energies released by several common chemical explosives (CE's) when tamped, and to measure the effects of a change in both dome and scale on the cavities produced by tamped bursts.

As part of Phase I, sixteen tamped spherical charges weighing ~ 20-30 grams (gm) each were fired in a salt dome at Hockley, Texas, and four 60-80 gm spheres in a dome at Grand Saline, Texas (where all the ground-motion measurements of the program were made). In addition, the Defense Advanced Research Projects Agency (DARPA) asked Applied Theory, Inc. (ATI) to aid in planning a concurrent series of DARPA-sponsored shots in pressed salt at the Lawrence Livermore Laboratory (LLL): earlier, we had worked with LLL personnel who sought (under DARPA auspices, at our request) to measure the energy released by Pelletol. At ATI's suggestion, the effects of variations in charge shape and confining pressure were measured at LLL during and after the Hockley tests. Together, the Phase-I and LLL experiments establish the difference between lab- and dome-salt in terms of cavity size - and, by inference, the difference between their shear-strength limits.

Six tamped spheres of PETN, six of TNT, two of nitromethane ("NM") and two of RDX, were fired at Hockley. After weighing a given charge and fitting it with a detonator near its center (plus lead wires, etc.), it was set tightly into a cavity reamed in a cylinder of salt. The resulting assembly was grouted into the hole left in the mine floor by removal of that same salt cylinder. After detonation, the final cavity volume was measured. At Grand Saline, similar (but not identical) procedures were followed with two tamped spheres of PETN and two of NM. [For details of the experiments, see Part II of this report.]

The method used to obtain the energy released by a given CE charge (and hence its energy-release, e_o, per unit mass), hinges on the measurement of ΔV_c, the change in cavity volume due to its detonation. The resulting e_o-value can be further refined if data are at hand from standard laboratory tests of that CE. In any case, knowledge of e_o and ΔV_c for one "standard" CE is essential. The deduction of e_o from these data is described at length below (Section 2.2).

PETN was used as the standard CE in Phase I. Its available energy had been measured to within 1% at LLL as 6.26 kilojoules (kj) per gram (gm), regardless of loading density or confinement. However (below), PETN becomes a very dangerous explosive in amounts 100 times as large as 30 gm, whereas, in charges weighing less than at least 5 kilograms (kg), Pelletol's energy release depends on mass. To measure e_o for Pelletol, the plan followed was therefore to first find e_o for a CE like nitromethane (NM), which can be used safely in Cowboy quantities and whose e_o-value is supposedly mass-independent down to the lower masses of Phase I. With its e_o-value known from Phase I, the next step was to detonate that safe CE in Phase II along

with Pelletol, in Cowboy-like amounts - thus permitting e_o to be deduced for Pelletol by the method of Phase I. At the same time, the Phase I shots play a vital role in quantifying the effects of scale and medium out to the laboratory limit.

1.2 Principal Results

The quantitites $\Delta V_c/m$, $\Delta V_c/E$ and e_o occur repeatedly below, where m is the mass of a CE charge, E is the work available from its detonation products under ambient conditions (its "energy release"), and $e_o \equiv E/m$.

With respect to explosive energy release, the main results of the Hockley experiments are these: For TNT, e_o has the value $3.93 \pm .05$ kj/gm at a loading density, ρ_o, of 1.59 gm/cc, and $3.29 \pm .08$ kj/gm when $\rho_o = 1.22$ gm/cc; for nitromethane ($\rho_o = 1.13$ gm/cc) $e_o = 4.31 \pm .13$ kj/gm; for RDX, the values found for e_o were 5.64 and 5.63 kj/gm at loading densities of 1.70 and 1.22 gm/cc, respectively. At Grand Saline, the Phase-I shots gave $e_o = 4.68 \pm .19$ kj/gm for NM. The uncertainties just quoted for e_o refer only to the scatter of e_o-values in multiple tests with the same CE and loading density. That scatter lies well within our present estimate of the probable error ($\pm$ 6%) in the underlying assumption made above that $\Delta V_c/E$ is constant. Also, the values of $\Delta V_c/m$ measured for PETN had a standard deviation of $\pm$ 3.2%. Accordingly (PETN aside), the estimated error in e_o is $\pm$ 6-7% in all cases. It should be noted, however, that the Phase I experiments at Grand Saline, with their larger charges, were the most difficult to perform; otherwise, the Grand Saline shots suggest a possible dependence of e_o on charge-size, for NM masses $\leq$30 gm.

Meanwhile, two results directly tied to Phase I were being obtained at LLL. Using 6-gm charges of LX04, a CE whose

e_o-value (5.50 kj/gm) was shown to vary little with confinement, cavities were blown in pressed-salt cylinders under static outside pressures of 60 to 320 bars. [For the Salmon, Cowboy, Hockley and Grand Saline events, values of overburden were 180, 60, 65 and 48 bars, respectively.] Within experimental error ($\pm$3%), there was no change in ΔV_c with static pressure. However, when the spherical charges of LX04 were replaced by Cowboy-shaped cylinders, ΔV_c increased by almost 15%.

Though independent of static stress, the LLL value of $\Delta V_c/E$ was only about half that measured at Hockley (.47 cc/kj vs. .99 cc/kj for PETN). That difference could be due mainly to different von Mises limits of strength (Y_{vm}) in the two salt media. In particular, simple power-law relationships between ΔV_c and Y_{vm} have been derived from computer experiments.[4,5] Taken with both Salmon data and the measured values of ΔV_c, the formulas imply a Y_{vm}-value for LLL salt about 1.3 times that actually measured in the lab (and about 2.4 times that of dome salt).

The data also suggest that if TNT were detonated at Pelletol density (1.0 gm/cc) in Hockley salt, $\Delta V_c/E$ would equal about .99 cc/kj; the three PETN charges with $\rho_o \approx 1.09$ gm/cc and the three with $\rho_o \approx 1.63$ gm/cc produced widely different pressures, etc., but gave almost the same mean values of $\Delta V_c/E$ (< 1½% apart). For the tamped Cowboy events, the measured value of $\Delta V_c/m$, corrected for charge-shape, is 3.39 cc/gm of Pelletol, while calorimetric and other data now available at LLL make it highly likely that e_o lies between 3.2 and 3.7 kj/gm. On that basis, $\Delta V_c/E$ lies between .92 and 1.06 cc/kj for Cowboy, as compared to .99 cc/kj at Hockley - the most direct evidence yet that final cavity volumes are insensitive to changes in dome and scale. [For Salmon,

$\Delta V_c/E$ had the somewhat lower value .88 cc/kj, presumably because NE (nuclear explosive) leaves more heat in surrounding solid than CE does.] Also, though study of the data continues, the Phase II and III events have given a cavity volume of 3.51 cc per gm of Pelletol, vs. 3.39 cc/gm for Cowboy - direct evidence that cavity volumes are dome-indifferent.

Two assumptions implicit in the Cowboy-Hockley comparison just made are that i) in dome-salt, just as in lab-salt, ΔV_c is unaffected by changes in static compressive stress, and ii) ΔV_c changes with charge-shape by about the same factor in the two salt media. The measurements made in Phase II, together with the results of Phase I, will quantify the separate effects of scale and overburden on ΔV_c in dome-salt (so far, the largest effect is an apparent e_o-increase of ~9% for NM, with increasing mass); if need be, the variation of ΔV_c with charge-shape can also be measured in situ.

1.3 The Significance of Path-Dependent Yield for Field Tests and Nuclear Monitoring

From data obtained during Cowboy Event 10, a decoupled shot, it was shown about six years ago[1] that the energy released by Pelletol was ~2.55 kj/gm, as opposed to the nominal value of 4.185 kj/gm for TNT. Subsequent calorimetric work at LLL gave the more accurate value 2.44 kj/gm for TNT after free expansion from Pelletol density, and 4.57 kj/gm in expansion against heavy inertial resistance. Thus, the energy released by TNT (the work its detonation products can do) varies with its conditions of confinement - whence also with its loading density - by almost a factor of two. Conclusion: The detonation products of TNT vary in composition, and therefore in energy, with the thermodynamic (volume-temperature) path taken in bringing

them to a given state. Yet, in nuclear monitoring and other DoD work, no field-test parameter is more important than yield. In turn, to specify yield for a CE burst, getting e_o right is clearly as necessary as getting the weight of the charge right. These facts supply part of the motivation for Phase I - and more generally, for measuring e_o under in situ conditions of detonation.

It makes physical sense to expect that, among possible expansion paths, heavy confinement (thick gold cladding at LLL) and no confinement (~350-fold expansion into an evacuated chamber at LLL) will give rise to extreme values of e_o (Appendix IA a). Accordingly, regardless of confinement, e_o can be estimated as the square root of the product of those values, with a maximum-error-factor equal to the square root of their ratio - an error-factor of "only" 1.37 for Pelletol. Among the reasons for refusing to live with that factor (or even a factor of 1.2) are these:

i) Yield is ubiquitous; e.g., it plays a key role in determining scaling rules, NE-CE equivalence factors and decoupling factors.

ii) Several properties of the Cowboy fields translate into seismic-source uncertainties as large as that due to the variable yield of TNT; e.g., owing to gauge drift, measured displacement spectra can be seriously in error at vital low frequencies. Given 3 or 4 such properties, RVP-spectral amplitudes could be too large or too small by factors of $1.37^3 \approx 2.6$ or $1.37^4 \approx 3.5$. Either the causes of error-factors that large are eliminated one by one, or - complex models notwithstanding - guesswork and qualitative discussion will continue to play a large role in source theory.

iii) By the method of Phase I, e_o can be found for a given CE at a small fraction (at most a few percent) of the cost of a

well-instrumented field test. Moreover, the number of CEs and CE-earth configurations of practical interest is also small, and e_o is not likely to vary significantly with changes in medium (pinning that variation down for at least one medium other than salt should be a future test-objective). Thus, in the future, in situ events will give rise less and less often to a need for determining e_o. However, if that need is not met, then in time (two or three years, perhaps), more will have been spent to estimate the effects of uncertainties in e_o, and to reconcile conflicting estimates, than would be needed to determine the e_o-values themselves. Thereafter, the cost of estimating and adjusting for errors will exceed by a growing factor what it would have cost to eliminate them.

iv) With specific reference to pelletized TNT: For good or ill, Pelletol was used as the Cowboy explosive. Further, the Cowboy series remains an unsurpassed source of data on explosively-driven ground motion. It would be hugely expensive to gather comparable data again, using an explosive whose energy is better known than Pelletol's. Thus, there is no realistic alternative to more precise determination of Pelletol's energy release in tamped Cowboy shots - especially since doing so presents no major technical problem (Section 2). Then, having already found the energy released by Pelletol in large cavities, Cowboy data can be used to shed light on such basic issues as decoupling, scaling, equivalence of salt domes, NE-CE equivalence, and the effects of overburden, free of significant uncertainties in yield.

At present, item iv) nullifies the observation that safe explosives are at hand whose energy release is not as variable as TNT's. That observation should be acted upon once

Pelletol's yield is known; better CEs than Pelletol or TNT can surely be chosen for future field tests. However, the frivolous idea of ignoring error-factors in yield that appreciably exceed 1.1, is itself best ignored.

Item (iii) also merits further comment. In particular, while not many e_o-values are needed, they have to be measured under conditions of detonation like those met in actual field tests. Under other conditions (e.g., cased cylinders detonated from one end), e_o can differ appreciably from the value for a centrally initiated sphere in rock. The immediate reason therefor lies in the tendency of inert CEs like TNT, which are relatively safe and widely used, to have expansion-path-dependent energies. By contrast, e_o varies by less than 1% with confinement and loading density for PETN (as noted in Section 1.2) - but PETN is too sensitive to consider using in amounts exceeding a few pounds.[6]

A general trend seems to oppose us here: CEs whose energies are fixed are touchier than CEs of variable energy. More suggestively put: When the same end products form under all conditions of detonation, their formation tends to be easily initiated. Oxygen balance has been cited as the main factor underlying that tendency [CEs which (like PETN) are nearly oxygen-balanced, are likely always to yield the same end products]. However that may be, safe CEs that buck the trend by having fixed energy, hold obvious interest for test events.

SECTION 2

DEDUCTION OF ENERGIES

2.1 Proportionality of Cavity Volume and Yield

For a contained burst of given yield, shear strength is generally thought to control the size of the resulting cavity. Indeed, cavity volumes can be computed with useful accuracy for nuclear bursts from just the von Mises limit of strength, Y_{vm} (taken here as the largest shear stress that can be borne in equilibrium by a given material for times on the order of a second). One such relation, summarizing the results of many calculations of wholespace motion[4], is the following:

$$V_c = .66 \times 10^6 \, W \, Y_{vm}^{-6/7} \qquad (8)$$

with the cavity volume V_c and yield W in cubic meters and kilotons (1 kiloton=4.185×10^{19}erg), and Y_{vm} in bars. Independently, in a more elegant and comprehensive study[5], it was found for nuclear explosions in halfspaces that

$$V_c = 1.05 \times 10^6 \, W^{7/8} \, P_o^{-1/4} \, Y_{vm}^{-3/4} \quad (W \geq 1kt) \qquad (9)$$

where P_o is the overburden pressure in bars. From the cavity volume (19,600 m^3), yield (5.31 kt) and overburden (180 bars) for the Salmon event, the values 229 and 263 bars, respectively, are obtained for Y_{vm} from Eqs. (8) and (9).

Formulas like (8) and (9) have apparently not been developed for chemical explosions, and the numerical coefficients on the right of Eqs. (8) and (9) may well change on passing from NE to CE. However, in the matter of most concern here - the

variation of volume with yield in dome salt - there is very little doubt that the correct exponent of W in such simple expressions is 1 for yields <<1kt. Indeed, the exponent is equal rigorously to 1 when 1) the medium obeys simple scaling rules, 2) the medium is homogeneous under burst conditions, and 3) the explosive obeys simple scaling rules.

The available data generally support the belief that Condition 1) is met by dome salt during cavity formation; some uncertainty on that score is occasioned by the Hockley shots (Section 2.2), but salt otherwise follows simple scaling rules, within experimental error (3-4%). As for Condition 2), the Grand Saline medium is chemically and structurally homogeneous, consisting of 98+% NaCl and ~1% annhydrite; no cracks, joints, hollow spaces or inclusions (e.g., brine), other than microscopic, have been found in it.[7] Less appears to be known about Hockley salt, and Gulf domes often (perhaps typically) contain some gas and brine pockets; yet, at the 30-gm scale of the Hockley shots, and within a few feet of the mine floor, it is quite unlikely that we fell afoul of such inclusions - and the Phase-I data give no hint of their presence. Overburden variation and the mine itself therefore loom as the main sources of inhomogeneity in the medium.

The charges of Phases I and II were buried at scaled depths ≥100 m/kt$^{\frac{1}{3}}$ at Hockley and ≥113½ m/kt$^{\frac{1}{3}}$ at Grand Saline (≥310 m/kt$^{\frac{1}{3}}$ in Phase II). Hence, using the longitudinal wavespeed of 4.7 m/ms measured at Grand Saline, surface reflections reached shot depth no sooner than 42½ ms/kt$^{\frac{1}{3}}$ at that site, and 48½ ms/kt$^{\frac{1}{3}}$ at Hockley. From the Salmon and Cowboy events, it appears that there is no significant change in free-field displacement after motion has proceeded for ~70 ms/kt$^{\frac{1}{3}}$, while peak displacements occur within 30½ ms/kt$^{\frac{1}{3}}$. The latter time is the more pertinent for

cavity formation; the fraction by which rebound reduces outward displacement from its peak value decreases as slant-range decreases, and is already small ten cavity radii from the shot. Moreover, in calculations made with a wide variety of material models for salt, cavity radii have varied by less than 1% of their final values at times ≥ 45 ms/kt$^{\frac{1}{3}}$. In addition, Salmon and Cowboy data imply that reflected-stress (tensile) amplitudes at shot depth were no greater than 275 bars at Hockley; they were actually much smaller, because bags of salt were laid down at ground zero. It is very unlikely that even a reflected stress of 275 bars would cause salt to fail in shear (Section 2.4), though it would certainly suffice to cause spalling. Actually, spall was observed at Hockley only near the surface (at ~1/10 of shot depth). At Grand Saline, where larger charges were placed in shorter cores, spalling was more severe, and evidently caused cavity volumes in Phase I to increase by ~10% - but if so, then roughly by that same amount in each case.

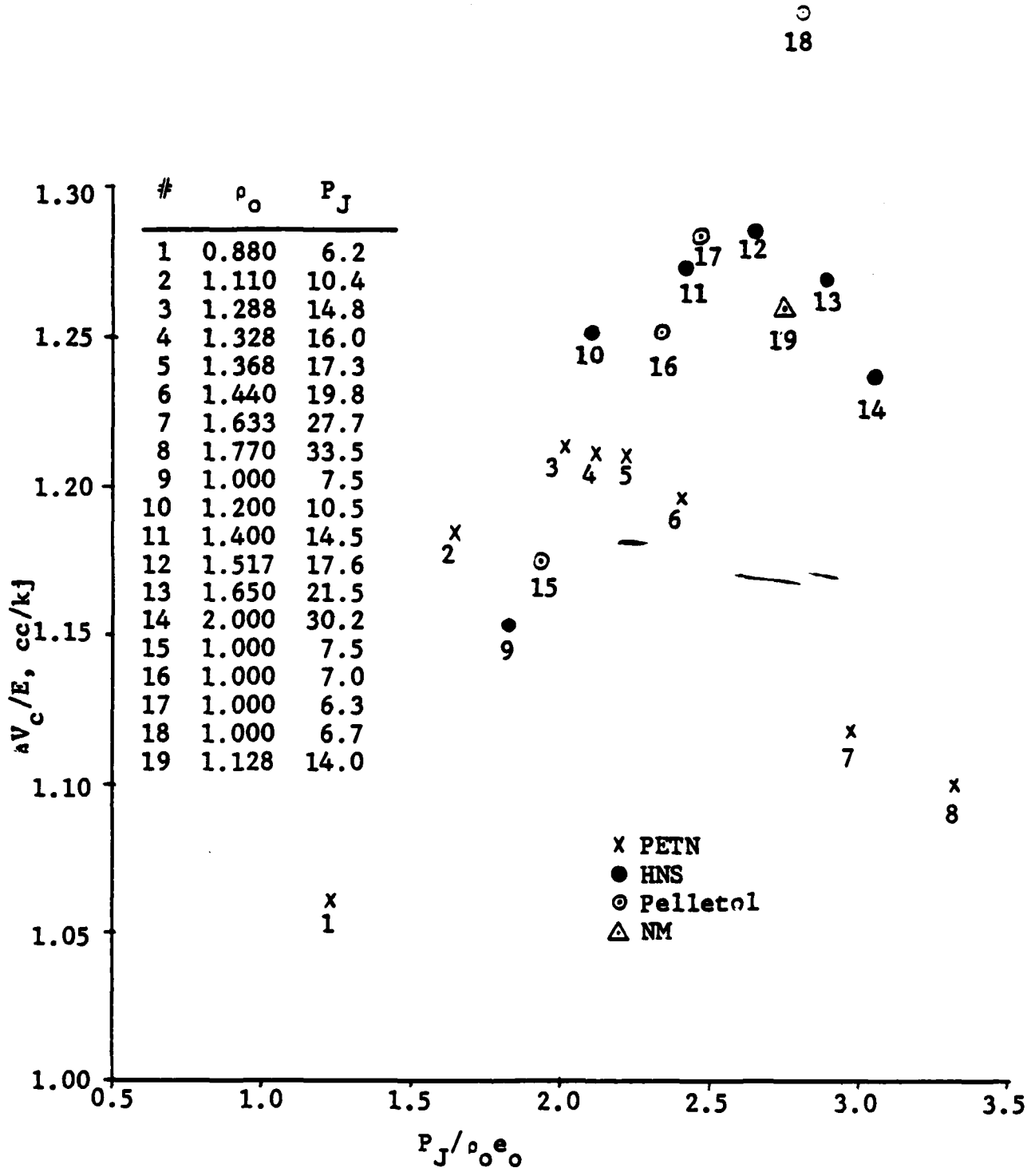
The effects of overburden variations on cavity volume were surely negliglible, because the most potent Cowboy Trails charge yielded less than an eighth of a ton of energy. At that yield, cavity formation is complete in ~2 ms (~1/20 of the time for 1 kt), at which point a cavity wall can have felt the influence of outside material no farther away than ~5 m. Considering the dimensions of the dome, and of the mine's drifts and pillars[7], variations of static in-situ stress (let alone overburden) are far too small over distances of 10 m (5 m in opposed directions) to play a significant role in cavity formation.

On the other hand, condition 3) above is unavoidably violated here: Detonations in different-sized-spheres of the

same CE can be simply-scaled versions of one another, but not detonations in two different CE's. For example, the Chapman-Jouguet detonation pressure (P_J) is 4-5 times higher in normal-density PETN than in Pelletol. The critical fact for the present method is that, as a determinant of cavity size in a given medium, total-energy-release far outranks all other variables - including P_J, with its range of a factor of 5 (or more). The point is illustrated in Fig.1, where values of $\Delta V_c/E$ calculated for many CE's in salt are plotted vs. $P_J/\rho_o e_o$. The latter quantity and Fig.1 will be discussed further below (Section 2.4); for the moment, the main burden of the figure is that the values of $\Delta V_c/E$ all lie within 10% of a central value (in this case 1.16 cc/kj). That result and its physical roots (which underlie such formulas as (8) and (9)), are the reasons for thinking that e_o can be found to within ~10% by measuring ΔV_c. In addition, for many CE's, independent data are available on the equations of state of detonation products. Using those data, it appears that the uncertainty in e_o can be reduced to 4 or 5% - but that reduction can not yet be made with confidence.

2.2 CE Energies from Phase I, Assuming Volume Growth Proportional to Yield

The Phase-I events at Hockley were completed early in 1980. Soon afterward, it developed that the Hockley mine would not be available for the other phases of the Cowboy Trails program. Arrangements were made to use the Kleer mine (Grand Saline) instead, creating a need for more Phase I shots: A data-set from one dome is essential in separating the effects of dome-changes from those of scale-changes (a major program goal). In addition, as discussed below, the Hockley experiments



#	ρ_o	P_J
1	0.880	6.2
2	1.110	10.4
3	1.288	14.8
4	1.328	16.0
5	1.368	17.3
6	1.440	19.8
7	1.633	27.7
8	1.770	33.5
9	1.000	7.5
10	1.200	10.5
11	1.400	14.5
12	1.517	17.6
13	1.650	21.5
14	2.000	30.2
15	1.000	7.5
16	1.000	7.0
17	1.000	6.3
18	1.000	6.7
19	1.128	14.0

FIGURE 1. Calculated Values of Cavity-Volume-Increase per Unit of Explosive Yield for CE Bursts in Dome-Salt, vs. a Non-Dimensional Pressure Parameter. E=total energy of explosive; ΔV_c =increase in cavity volume; ρ_o and e_o, respectively, are the density and the available energy per unit mass, of the undetonated explosive. All points are numbered, and the values of ρ_o (gm/cc) and P_J (kj/cc) are tabulated for each. [1 kj/cc = 1 GPa = 10 kb]

raised some questions that made it desirable to conduct other Phase-I events - and, early in 1983, four such shots were fired in the Kleer mine.

The main data from all Phase-I shots are listed in Table 1. Also listed are e_o-values obtained by treating $\Delta V_c/E$ as a constant whose value is fixed by the Phase-I measurements for PETN (and its known e_o-value, 6.262 kj/gm); since $E=me_o$, e_o is then obtained for other CE's from the simple formula

$$e_o=(E/\Delta V_c)_{PETN}(\Delta V_c/m) \qquad (3)$$

Two values of cavity-volume-increase, denoted ΔV_c and ΔV_c^*, appear in Table 1 for each Phase-I event, along with energies e_c and e_o^* derived therefrom [via Eq.(3)]. For Hockley, the values of ΔV_c include a correction of 7.4 cc to account for space under rubble that falls into the cavity during re-entry (and perhaps earlier) - space not penetrated by the sand used to measure cavity volume. That correction is absent from the data-table of Part II of this report, and from the subsequent discussion of measurement-accuracy. We were told of it shortly after PAI submitted to DARPA a draft report on the Hockley experiments. Said report, which comprises Part II below, was apparently prepared before discovery of the 7.4 cc correction, and thereafter was not revised to include it.[8] The adjustment remains a valid one as far as we know, but we cannot be definitive about it. Table 1 therefore includes the values of volume growth and detonation energy (denoted ΔV_c^* and e_o^*) that result from its omission.

2.3 Sources of Uncertainty in the e_o-Values of Table 1

The main cause for concern with the Hockley data in Table 1 is that the final e_o-value for NM (4.31 kj/gm) is a good deal lower than the calorimetric value of 5.13 kj/gm for heavily clad NM charges[9] - and appreciably below the older value of

TABLE 1

PHASE I EVENTS AND SOME OTHERS:

CAVITY VOLUMES AND THE CE ENERGIES FOUND FROM THEM

Shot #	CE NAME	m gm	ρ_o gm/cc	V_c cc	ΔV_c^* cc/gm	ΔV_c cc	$\Delta V_c^*/m$ cc/gm	$\Delta V_c/m$ cc/gm	e_o^* kj/gm	e_o kj/gm	Averages
HOCKLEY - PHASE I											
1	TNT	26.4	1.575	112	94.5	101.9	3.58	3.86	3.70	3.86	ρ_o=1.589
2	TNT	27.0	1.611	117	99.5	106.9	3.69	3.96	3.82	3.96	e_o^*=3.78
3	TNT	26.5	1.581	115	97.5	104.9	3.68	3.96	3.82	3.96	e_o=3.93
4	TNT	20.0	1.193	74	56.5	63.9	2.825	3.195	2.95	3.21	ρ_o=1.208
5	TNT	20.5	1.223	79	61.5	68.9	3.00	3.36	3.14	3.375	e_o^*=3.05
6	TNT	20.3	1.211	(50)	(32.5)						e_o=3.29
7	PETN	27.0	1.611	183	165.5	172.9	6.13	6.40	6.262	6.262	
8	PETN	28.0	1.671	178	160.5	167.9	5.73	6.00	6.262	6.262	
9	PETN	27.1	1.617	181	163.5	170.9	6.03	6.31	6.262	6.262	
10	PETN	19.4	1.11	124	106.5	113.9	5.49	5.87	6.262	6.262	
11	PETN	18.5	1.06	128	110.5	117.9	5.97	6.37	6.262	6.262	
12	PETN	19.1	1.09	129	111.5	118.9	5.84	6.225	6.262	6.262	
13	NM	19.5	1.13	91	73.5	80.9	3.77	4.15	3.98	4.18	e_o^*=4.13
14	NM	20.0	1.13	98	80.5	87.9	4.025	4.395	4.27	4.43	e_o=4.31
15	RDX	28.5	1.700	171	153.5	160.9	5.39	5.65	5.56	5.64	
16	RDX	20.5	1.223	125	107.5	114.9	5.24	5.60	5.51	5.63	
GRAND SALINE - PHASE I											
2	PETN	75	1.09	523	391	454	5.21	6.05	6.262	6.262	
3	NM	77	1.13	425	293.4	356.4	3.81	4.63	4.58	4.79	e_o^*=4.45
4	NM	77	1.13	408	276.4	339.4	3.59	4.41	4.31	4.56	e_o=4.68
GRAND SALINE - PHASES II AND III											
		(kg)		(liter)		(liter)					
1	PLTL	74.8	.870	336		250		3.34			
2	PLTL	78.2	.876	367		277½		3.55			
4	NM	98.4	1.13	527		439		4.47			
5	NM	89.8	1.13	506½		426		4.74			
III	PLTL	86.6	.870	415		316		3.65			

4.53 kj/gm, derived from the axial detonation of cylindrical charges in pipes[10]. The gap of ~13% between 4.53 and 5.13 kj/gm (while much smaller than the known range of e_o for TNT) is another case of variation of e_o with expansion path. There is no reason to suspect either value for NM, and the NM shots of Phase I were not fired to test them; rather, the purpose of those shots was to provide a uniform data-base from which to derive a value of e_o for Pelletol - and, in the process, to find a more precise value of e_o (expected to lie between 4.53 and 5.13 kj/gm) for tamped, center-lit, spherical charges of NM. Instead, Table 1 presents an e_o-value 5% below the lower of those two (4.53 kj/gm), and 10% below it if e_o^* replaces e_o. Even those results might readily be accepted as due to error in the assumption of constant $\Delta V_c/E$ for Phase-I bursts, except that PETN and NM are both well-studied explosives (in contrast with Pelletol). Not only have their e_o-values been measured independently of the Phase-I tests, but their JWL coefficients as well. As a result it need not be assumed that $\Delta V_c/E$ has a single value for all CE's; the ratio of calculated values of $\Delta V_c/E$ can be used to correct for detailed differences between CE's - whence Eq. (3) becomes

$$e_o = r_{12}(E/\Delta V_c)_{PETN}(\Delta V_c/m) \qquad (4)$$

where r_{12} is the calculated value of $\Delta V_c/E$ for PETN, divided by the calculated value of $\Delta V_c/E$ for the second CE (NM, in the present case).

As Fig. 1 shows, detailed calculations of bursts in dome salt, using the known equations of state of PETN[11] and NM, yielded values of $\Delta V_c/E$ that were among the lowest and highest found (1.12 cc/kj for PETN with ρ_o=1.63; 1.26 cc/kj for NM). With r_{12}= 1.12/1.26 for the NM bursts of Phase I at Hockley, e_o drops to 3.83 kj/gm and e_o^* to 3.67 kj/gm [Eq. (4)], or .85 and .81 of the lower limit (4.53 kj/gm) of e_o's expected range. These energies

can have three obvious meanings (or combinations of them): i) e_o does lie well below the range $4.53 \leq e_o \leq 5.13$ kj/gm. ii) The ratio of calculated values of $\Delta V_c/E$ for PETN and NM is in error by 20-25%. iii) The measured values of ΔV_c are too low for NM, relative to PETN.

The first interpretation is implausible - though not out of the question, since calorimetry is lacking for bare NM. However, NM's oxygen-balance-index[12] ("OB") is almost the same as that of BTF (-39 vs. -38), and values of e_o have been measured in the calorimeter for bare and heavily clad charges of several different CE's, including BTF.[9] Interpolating in those data [e_o(bare)/e_o(clad), vs. OB] gives e_o=4.07 kj/gm for bare NM (Appendix IA 2). Even that value is higher by 6% and 11% than the ones to be accounted for (3.83 and 3.67 kj/gm) - and those percentages are deceptively modest: The true lower bound on e_o afforded by bare CE stems from a constant-energy expansion (a thermodynamic "free expansion"). By contrast, NM lost 3/4 of its energy to salt in the calculation that gave the point shown for NM in Fig. 1 - less than the almost-total loss experienced by heavily clad CE in the lab, but probably closer to that limit than to no loss at all (bare CE), in terms of detonation products.

As for ii) above, equations of state of dense mixtures of reacting gases can only be approximate; in fact, the program goal from which this whole discussion stems is that of narrowing the uncertainty in an equation-of-state parameter (e_o). However, a variation of 20-25% spans the range covered by $\Delta V_c/E$ for all the CE's of Fig. 6; its cause is therefore not likely to lie with errors in the JWL equations of state for NM and PETN. In support of that view, the value of ΔV_c calculated for PETN with ρ_o=1.63 is larger than for ρ_o=1.085 by ~1%, as compared to 1.3% measured at Hockley. [Absolute values of $\Delta V_c/E$ depend on the assumed properties of salt (Eqs. (1),(2)), and hence shed no

added light on e_o or its sources of error; as it happens, ΔV_c (calculated) exceeds ΔV_c (measured) by a factor of 1.12 if the correction of 7.4 cc is made, and 1.18 if it isn't.] Conclusion: The values of ΔV_c measured for NM are most likely lower than they should be relative to PETN [iii), above]. A physical basis for that conclusion was suggested by PAI's principal investigator for Phase I: Much of the NM in a charge as small as 30 gm may undergo low-order detonation before Chapman-Jouguet conditions are reached. Accordingly, the extra Phase-I shots fired at Grand Saline had larger charges than at Hockley (Table 1) - by a factor of ~4, in the case of NM.

For the Grand Saline cavities, values of $\Delta V_c/E$ proved higher than the Hockley values by ~8%. However, while the scaled depth of burial of the Grand Saline charges was ≥113½ m/kt$^{\frac{1}{3}}$ (Section 2.1), the top 2/5 of the space above each charge was filled with crushed salt, out to a horizontal radius equal to ~1/5 of the burial depth [Appendix IIA]. Crushed salt being much softer than solid dome-salt (and somewhat less dense), a strong rarefaction was reflected from the crushed-salt/ solid-core interface; further, relative to that interface, the charges were buried at scaled depths of only 58 m/kt$^{\frac{1}{3}}$ (PETN) and 63 m/kt$^{\frac{1}{3}}$ (NM). Not surprisingly, spalling was more severe than at Hockley; a section of one core shattered, while the others came apart over appreciable distances in the horizontal plane at shot depth, where core-sections had been glued together. Moreover, waves reflected from the core-crushed-salt interface reached the cavity at ~25 ms/kt$^{\frac{1}{3}}$ after detonation, when cavity formation was not yet complete. Hence, more complex processes influenced the development of cavities at Grand Saline than at Hockley, and a wider variety of material properties was exercised (including the strength of epoxy glue). However, the resulting cavities were still predominantly spherical, extending

further in the vertical direction than the horizontal by only 7-14% (horizontal diameters are not specified by event in Appendix IIA). The crack's length at shot horizon was ~3/7 of the cavity radius in that plane, but it added only ~3% to the cavity volume. Further, the scaled depths of burial for PETN and NM differed by less than 10%, and the core/crushed-salt interface was first seen by the cavity after most of its growth had already occurred. The hypothesis of constant $\Delta V_c/E$ should therefore be almost as valid for the Grand Saline cavities as at Hockley, and the e_o-values for Grand Saline in Table 1 were computed on that basis. In addition, the contribution made by vertical elongation to the post-shot cavity volume, V_c, was subtracted from ΔV_c to give ΔV_c^* and the detonation energy e_o^* derived from it (that contribution was estimated as 50+13=63cc, in accord with Appendix IIA). In doing so, our intent has not been to correct e_o, but simply to show how the cavity's asymmetry affects it; in contrast with the corresponding Hockley data in Table 1, ΔV_c^* and e_o^* for Grand Saline are not to be taken as alternatives to the quoted values of ΔV and e.

Since e_o can hardly be less than ~4.07 kj/gm, and the Hockley and Grand Saline data are both subject to appreciable uncertainty, our best estimate of e_o for NM is an average of the e_o-values obtained from the two sets of Phase-I events, or 4.50 kj/gm; the uncertainty in that number is probably ≤ 4.50-4.13=.37 kj/gm, or $\pm$8%. Also, with e_o=4.50 kj/gm for NM, the Phase-II values of $\Delta V/m$ (Table 1) imply that, for Pelletol, $e_o \approx 3.43$ kj/gm - as will be discussed in detail in the forthcoming report on Phase II.

2.4 The Variability of $\Delta V_c/E$

For CE, the single property most closely correlated with cavity volume is yield; for the medium, the key property is the von

Mises limit of shear strength. However, neither relation is one-to-one; formulas like (1) and (2) are not exact, nor do they need to be here: By the method used above, detonation energy is deduced from the ratio of cavity volumes created by two CE's (e_o being known for one of them). In our calculations, that ratio has proven insensitive to the properties of the medium - a good thing, since models of geologic solids (despite their complexity) are quite primitive. Thus, $\Delta V_c/E$ was found constant to within 10% for tuff just as for salt (a very different material), though for tuff $\Delta V_c/E$ was higher for PETN than NM, rather than lower. No large variation in the ratio of $(\Delta V_c/E)$-values has been seen yet among ATI's various salt models, but the point bears further inquiry.

The dependence of $\Delta V_c/E$ on CE is significant, as Fig. 1 shows, and the accuracy of the present method can only be improved by taking it into account. The ratio r_{12} of $(\Delta V_c/E)$-values for two CE's ("1" and "2") expresses that dependence in the most directly useful way here. The central fact is that $r_{12}\approx 1$, but r_{12} does vary by at least 10%, and is a measure of the relative efficiency of CE's for cavity-volume creation; for a given total energy release, CE #1 creates larger cavities than CE #2 if $r_{12}>1$ and smaller cavities if $r_{12}<1$. The quantity $P_J/\rho_o e_o$, chosen as the abscissa of Fig.1, represents a first guess as to what CE property might correlate well with r_{12}. Specifically, $\rho_o e_o$ is the available energy per unit volume of CE, and is equal to the pressure of ideal-gas products in a constant-volume detonation (apart from a numerical factor); since cavities form mainly as a result of shear failure in the medium around them, it was thought that the higher the Chapman-Jouguet pressure relative to the available energy per unit volume, the more efficient a CE might be at creating cavity volume. Indeed, if P_J were too low to cause shear failure, the cavity would hardly grow at all. The argument gains further strength in that, at the moment when CE-medium interaction starts, the flow of detonation products

is given always by Taylor's solution; the large difference between Taylor flow and constant-volume detonation (for example) can affect cavity volume as much as $P_J/\rho_o e_o$ - but it doesn't arise. Nevertheless, as more points were added to Fig. 1 during the program, the basic idea proved overly simple; e.g., for PETN at various loading densities, $\Delta V_c/E$ grows at first with $P_J/\rho_o e_o$, and then falls.

To see why the plot has thickened, note that we increase $P_J/\rho_o e_o$ for PETN (and other CEs) by raising ρ_o; $\rho_o e_o$ then grows, but more slowly than P_J. The upshot is not just to ensure shear failure in the medium, but also to enhance shock heating (irreversible work done on the medium by the stress driving the shock). Of course, heating occurs during shear failure as well, with irreversible work done by shear stress. Shear stress, however, is limited by the strength of the medium, while the stress that drives the main outgoing shock is limited only by the pressures CE's can generate. Those pressures far exceed the strengths of geo-materials (salt included). Raising P_J therefore takes shock heating from a negligible effect to a major mechanism and the chief mode of energy dissipation. Hence, as P_J grows, so does the factor by which the main shock decays in moving outward a given number, n, of charge radii (the system's only scale of distance). Even so, with higher initial pressure at the charge-medium boundary, shock pressure generally stays higher after n radii of travel. However, the <u>distance</u> spanned by n charge-radii shrinks as $\rho_o e_o$ (or P_J) grows: CE's must be compared on the basis of equal energy release, whence initial CE volumes stand in inverse ratio to their $\rho_o e_o$-values. Thus, as P_J grows, a fixed distance R from the charge-center subtends a growing number of charge radii; the shock pressure at R ultimately begins to fall - and with it the maximum shear-failure distance and $\Delta V_c/E$.

These statements are borne out by the detailed calculations on which Fig. 1 is based. They can also be verified more simply

for uniaxial motion. Conclusion: The inherent error of the present method can be cut by a factor of 2-2½ if $\Delta V_c/E$ is treated as a function of $P_J/\rho_o e_o$, provided that P_J does not exceed a certain medium-dependent value, P_α. For salt, $P_\alpha \approx$ 160 kb, and a straight line runs within ~ 4% of all points of Fig. 1 for which $P_J \leq P_\alpha$. Specifically:

$$(\Delta V_c/E) = a + b(P_J/\rho_o e_o) \; ; \; P_J \leq P_\alpha = 160 \text{ kb} \qquad (5)$$

where least-squares fitting yields the values .89 cc/kj for a and .154 cc/kj for b.

Since the constants a, b and P_α are medium-specific, the points of Fig. 1 for NM and PETN (ρ_o =1.633 gm/cc) were recalculated for a much weaker salt. On that unlikely basis, r_{12} (whose value in Fig. 1 is 1.13) falls to 1.07; the adjusted values of e_o and e^* above (3.83 and 3.67 kj/gm) rise to 4.04 and 3.88 kj/gm - and thus remain puzzlingly low. Within reason, other variations should be made in the salt model (e.g., in its thermomechanical properties), and the points of Fig. 1 recomputed, to fix the uncertainties in Fig. 1, a, b and P_α. At present, Eq. (5) and Fig. 1 contain the best estimates now at hand for $\Delta V_c/E$ in dome salt - and since r_{12} [Eq. (4)] came directly from the calculations on which Fig. 1 and Eq. (5) are based, neither of them can tell us why the resulting values of e_o and e_o^* are so much lower than expected. Rather, Eq. (5) simply heightens interest in the question, since it implies (with Fig. 1) that the intrinsic error of the present method amounts to < 5%. In achieving that accuracy, PETN might have to be fired in a given medium at two different loading densities (with $P_J \leq$ 160 kb), to get a and b. More likely, b and P_α will prove insensitive to reasonable changes in the computational model of salt; firing PETN at just one density would then suffice to calibrate the medium.

SECTION 3

CONCLUSIONS AND RECOMMENDATIONS

Treating cavity-volume-growth per unit energy release ($\Delta V_c/E$) as a constant for contained spherical CE bursts in dome salt, the data from Phase I of the Cowboy Trails program have given an e_o-value of 4.50 kj/gm for nitromethane (NM). Moreover, the secondary goal of Phase I has been gained in fair measure: Within the scatter of data ($\sim\pm 8\%$, due mainly to uncertainty in e_o for Pelletol), the change of dome and scale from Cowboy to Cowboy Trails, Phase I, had no effect on cavity volume. [Likewise, Phases II and III (and Cowboy) establish that a change of dome alone has no effect on cavity volume, within measurement error ($\sim 4\%$).] Changes of dome and scale were attended by a small change in overburden (< 12 bars in all cases), but LLL data show that cavity volume varies negligibly over much larger ranges of confining pressure than that; be it noted also that LLL data on the variation of ΔV_c with charge shape, and on the energy release of Pelletol, enter the Cowboy/Phase-I comparison.

The accuracy of 4.50 kj/gm for NM's energy release is hard to assess; use of all the available information on PETN and NM raises questions for which we have no pat answers: i) $\Delta V_c/E$ is only roughly constant. The most plausible correction for variability of $\Delta V_c/E$ reduces the e_o-estimate for NM from 4.50 to 3.83 kj/gm - which is below the bound set by free expansion of gas (~ 4.07 kj/gm). Such an unreasonably low e_o-value (3.83 kj/gm) may signify delayed attainment of Chapman-Jouguet conditions in NM, a scale effect of little interest in nuclear monitoring (changes in the medium's properties with scale are of interest). Then again, a drop from 4.5 to 3.8 kj/gm could stem from errors

in the medium's constitutive equations and in CE equations of state. As a practical matter, such errors may even preclude correcting $\Delta V_c/E$ for its variation with CE and medium; we think not - but if so, then an e_o-uncertainty as large as 10% would have to be accepted for the in-situ detonation of NM spheres. ii) An experimental adjustment of uncertain accuracy has been made in the Hockley values of ΔV_c. No cores were obtained from Hockley, and its cavities have not been examined directly. Yet, without the adjustment, e_o for NM falls further (by ~.17 kj/gm). iii) All Phase-I cavities at Grand Saline were altered by surface reflections. As a result, it may be misleading to compare their values of $\Delta V_c/m$ to the rest, without knowing how much reflected waves affected cavity volumes.

In sum, $\Delta V_c/E$ varies enough so that, to find e_o for NM to within ~5%, the difference between the values of $(\Delta V_c/E)$ for NM and PETN must be determined to within a factor of ~3/2. The fact that we have so far been unable to fix the difference that accurately, most likely means one (or more) of three things: 1) scale effects in the detonation process may be thwarting our attempts to find e_o for NM by calculating the ratio r_{12} of $(\Delta V_c/E)$-values for NM and PETN; 2) measurement errors, especially in final cavity volume, may be producing the same net result; 3) in practice, it may not be feasible to reduce the uncertainty in e_o to < 10% by calculating r_{12} for NM, relative to PETN. The first possibility seems well suited to laboratory evaluation; to evaluate the second calls at least for recovery of cores from Hockley; it should be possible to evaluate the third via calculations that show how sensitive $\Delta V_c/E$ is to uncertainties in CE equations of state and in the constitutive equations for dome-salt.

APPENDIX IA

THE ENERGY OF NM AFTER FREE EXPANSION

1. Variability of Energy Release for CE's whose Detonation Products are not in Thermodynamic Equilibrium.

The chemical composition of a system is specified by the relative concentrations of its molecules and molecule-ions (in moles/liter, say). Under conditions of thermodynamic equilibrium, those relative concentrations are powerfully constrained: If the relative numbers of different atomic nuclei in any system are fixed, then the composition of the system is uniquely determined by its density and temperature. In the case of TNT's detonation products, the fact is that different compositions are measured after expansion to the same final density, ρ_f, and temperature, T_f, when different density-temperature paths are taken in reaching ρ_f, T_f. It follows that the final state is generally not one of thermodynamic equilibrium (as noted, only one composition is possible under thermodynamic-equilibrium conditions).

Relative to the composition at equilibrium, all others are metastable; in time, the others will approach that of thermodynamic equilibrium - but the universe may not last that long. In the short run, which in practice may mean "forever", chemical reaction rates can dictate that the compositions seen are not those of thermodynamic equilibrium. That is, some of the chemical reactions through which equilibrium is achieved may proceed so slowly at temperatures and densities of interest, that equilibrium compositions are not approached closely during times of interest (e.g., without a spark to activate them, two moles of H_2 and one of O_2 can stay mixed "indefinitely" at standard conditions, without reacting).

Of the two variables (density and temperature), common experience leads us correctly to conclude that reaction rates are more sensitive to temperature (quantitatively, they are roughly proportional to the Boltzmann factor $\exp(-\epsilon/kT)$, where ϵ is an activation energy and k is the Boltzmann constant). Thus, the variable energy of Pelletol and other oxygen-deficient CE's has been explained by noting that as the detonation products expand and cool, densities and temperatures are reached at which the rates of some reactions, at least, are too low for thermodynamic equilibrium to be maintained. Since temperature is the dominant variable, those reactions are said to be "frozen out" of the set through which equilibrium is achieved;[12] in fact, the entire composition can become "frozen" (i.e., change at a negligible rate at ambient temperatures and densities).

The cases given most attention in calorimeters are those of heavily clad CE and freely expanding CE. The two have important similarities in that a) the expansion of detonation products is adiabatic, and b) the temperature falls in roughly the same way during both expansions (reaction rates are critical here - not rates of expansion, which can be altered by mere changes of scale). Nevertheless, there is also a key difference between them:

i) When heavily clad products reach their final volume, they have given up nearly all their energy to the cladding around them. As a result, they stay cold; if composition has become frozen during expansion, it remains frozen after final volume is attained. The kinetic energy of cladding is converted to heat on collision with the calorimeter walls, and, through those walls, pieces of cladding slowly reach thermal equilibrium with calorimeter fluid (so do the alread-spent detonation products).

ii) During free expansion (by contrast), no energy leaves the detonation products. Instead, internal energy of the hot products is converted to kinetic energy of those same products, causing them to cool and their composition to freeze. They then collide with the calorimeter's wall, but, having expanded several-hundred-fold, they generate pressures too low to do significant work on it (or damage it). Hence, after the detonation products (mainly gases) are brought nearly to rest by a few shock reverberations, their mean internal energy is not sensibly different than the energy stored in the undetonated charge. In short, as they come to rest, those products become hot (if they were ideal gases, they would become about as hot - on average - as in a constant-volume detonation). Reactions frozen out during expansion can then proceed, taking the products to (or at least toward) their equilibrium composition, before their heat is slowly bled away into calorimeter fluid.

The two cases are extremes with respect to the composition of detonation products. Heavily clad, those products give up almost all their energy to the cladding and stay cold; hence, under adiabatic conditions (no exchange of heat with external systems), they could hardly be colder, nor their composition farther out of equilibrium. On the other hand (unconfined), they lose no energy during free expansion; as a result, (under adiabatic conditions) they could hardly be hotter - and hence closer to thermodynamic equilibrium - than when they come to rest. Thus, the composition of end products could hardly be more different (under adiabatic conditions) than in these two cases. While the two are not necessarily extremes with respect to the available energy of detonation products (e_o), that's certainly a safe bet.

2. Oxygen Balance

CHON-explosives (i.e., explosives consisting of carbon hydrogen, oxygen and nitrogen) are said to be oxygen-balanced when they contain enough oxygen to tie up all their carbon in CO_2 molecules and all their hydrogen in H_2O molecules. The term "oxygen balance" has also been extended to CHONF-explosives, which contain fluorine in addition to the other four elements; the generalization rests on the fact that fluorine, like oxygen, is an electron-acceptor, and that fluorine is found almost entirely as HF in the detonation products of CHONF-explosives (to the extent that hydrogen is available). Thus, a quantity called "oxygen balance" has been defined as follows:

$$OB(\%) = [d-2a-\tfrac{1}{2}(b-e)](1600/MW) \qquad (6)$$

where a,b, etc. are the numbers of atoms in the molecular formula $C_aH_bN_cO_dF_e$ for the explosive, and MW is its molecular weight. Formula (6) gives the percentage of the mass of CE which, if removed from or added to the CE in the form of oxygen, would make available just enough O- and F-atoms to tie up all C- and H-atoms in molecules of CO_2, H_2O, HF and CF_4.

Detonation energies have been measured calorimetrically for nine different CE's, both bare and thickly clad in gold.[9] For NM, unfortunately, e_o was measured only with heavy cladding. We therefore set about relating a) e_o for bare charges, b) e_o for heavily clad charges, and c) oxygen balance, OB(%). To do that, we turned to the cases in which e_o was measured for both bare and confined charges of the same CE. The results are shown in Fig. 2, where the ratio $e_o(\text{bare})/e_o(\text{clad})$ is plotted vs. OB(%). The various CE's are identified in the figure by their nicknames; Ref. 9 contains their proper names and formulas.

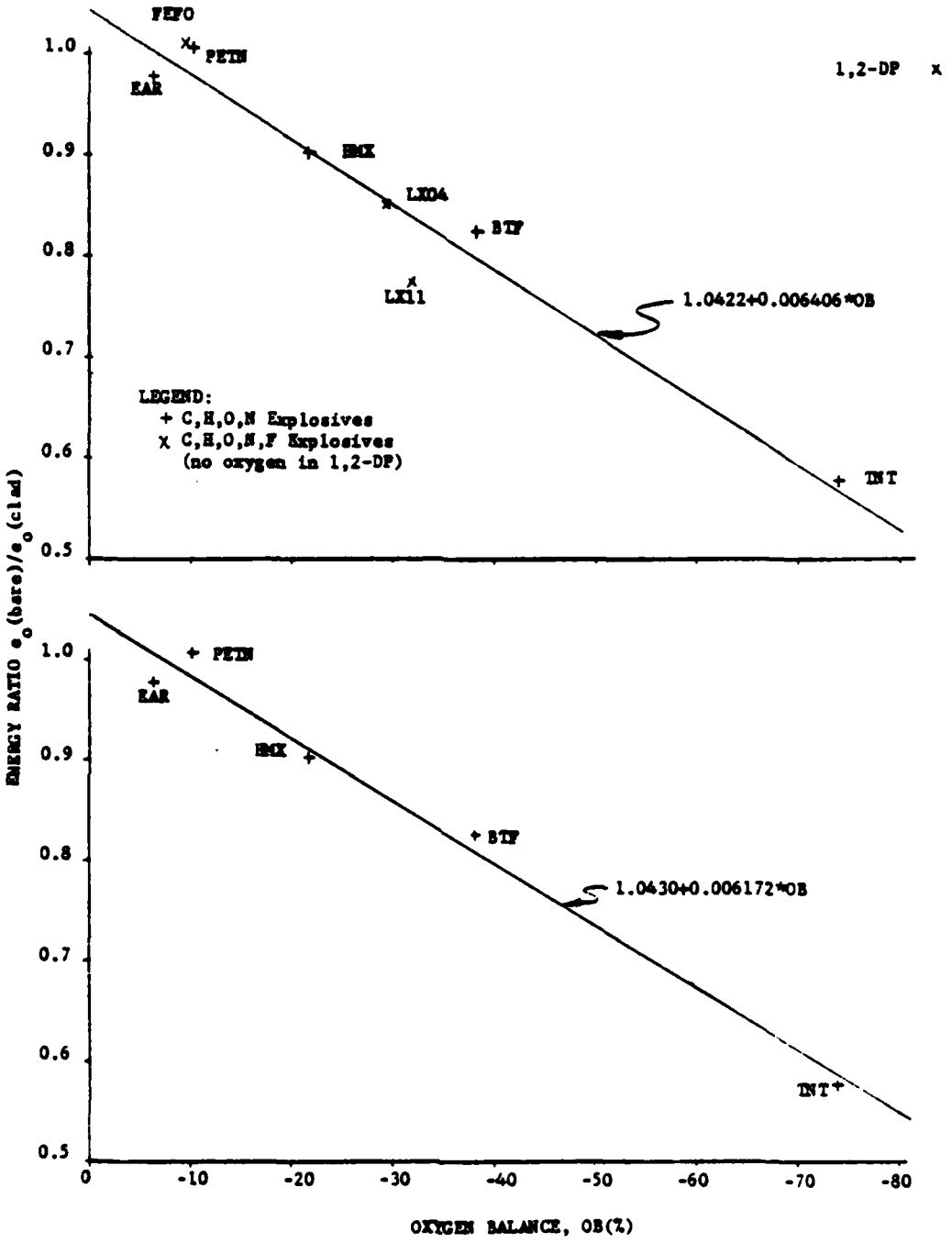


Figure 2. For Various Explosives: Ratio of Energies Released by Bare and Heavily Clad charges, vs. Oxygen Balance. Least-squares straight lines through the data-points are shown, excluding the point for 1,2-DP (upper plot). No fluorine-containing explosive is represented in the lower plot.

From the point in Fig. 2 for 1,2-DP - a CE that contains fluorine but no oxygen - it is clear that fluorine is not at all equivalent to oxygen with regard to the effects of confinement on detonation energy: Though 1,2-DP has the lowest (most negative) oxygen balance of all the CE's of Fig. 2, there is no significant difference between the detonation energies of bare and clad 1,2-DP. It seems that each F-atom runs off with an H-atom at or near the detonation front - and when no more H-atoms are left, F-atoms form CF_4 molecules with carbon. The resulting mixture of elements and compounds is thereafter virtually unreactive. Hence, if it were possible to form CE's by substituting two F-atoms for each O-atom in the materials of Fig. 2, it appears that $e_o(\text{bare})/e_o(\text{clad})$ would very nearly equal 1 in all cases. The fact that the other unbalanced CHONF-explosives LX04, LX11) fit in fairly well with the CHON's of Fig. 1, is probably due to their large number of O-atoms relative to half their number of F's ($d/\frac{1}{2}e = 8.8$ for LX04 and 6.3 for LX11). Even so, in view of the major difference between F and O disclosed by 1,2-DP, we have also plotted $e_o(\text{bare})/e_o(\text{clad})$ for the five CHON-explosives of the set. The least-squares line through the full set minus 1,2-DP, is as follows:

$$e_o(\text{bare})/e_o(\text{clad}) = (1.042\pm.018)+(.00641\pm.00060)(OB) \quad (7)$$

From the CHON-data alone we obtain

$$e_o(\text{bare})/e_o(\text{clad}) = (1.043\pm.018)+(.00617\pm.00045)(OB) \quad (8)$$

For NM, OB=-39.34 and $e_o(\text{clad})$=5.13 kj/gm, whence Eqs. (7) and (8) yield the respective values 4.05 $\pm$.13 and 4.11 $\pm$.09 kj/gm for $e_o(\text{bare})$. The latter value is adopted here because the presence of fluorine with oxygen complicates three of the CE's that contribute to the former - but in any case e_o needs to be measured for bare NM.

REFERENCES

1. J. Trulio, "Simple Scaling and Nuclear Monitoring", ATR-77-45-2 (Final Report on Phase IV of Contract No. DNA001-75-C-0304; April 1978).

2. D. Larson, "Inelastic Wave Propagation in Sodium Chloride", Bull. Seis. Soc. Am., Vol. 72, No. 6, pp. 2107-2130 (Dec. 1982).

3. For explosions in salt, inelastic deformation at stress amplitudes far below those associated with shear failure appears to have been recognized first by J. Trulio: "Overdrive Calculations Related to Nuclear Explosions", DNA 3542F (Final Report for Contract No. DASA01-70-C-0074; 18 June 1975). To our knowledge, speculation as to the physical origin of such deformation (and supporting calculations) also began with that report.

4. J. Trulio, N. Perl and R. Latham, "Limitations on the Size of Ejecta Craters", DNA 4253F (Final Report for Contract No. DNA001-75-C-0298 from 4/1/75 - 7/31/75; November 1975).

5. R. Terhune and H. Glenn, "Estimate of Earth Media Shear Strength at the Nevada Test Site", UCRL-52358 (Nov. 3, 1977).

6. E. Lee; private conversation.

7. R. Balk, "Structure of Grand Saline Salt Dome, Van Zandt County, Texas", Bull. Am. Assoc. of Petroleum Geologists, Vol. 33, No. 11, pp. 1791-1829 (Nov. 1949).

8. The portion of Table 1 that applies to Hockley was presented at the meeting of 28 May 1980 in Santa Monica, CA, called by the Defense Advanced Research Projects Agency (DARPA). As stated by Dr. Ford in a letter to DARPA dated 11 August 1982, PAI's report on Phase II "...was first submitted to DARPA (George Bulin) 15 May 1980. It was to be part of the final report to be prepared by ATI. There have been a few minor modifications of the report as requested by ATI, but nothing really has changed."

9. D. Ornellas, "Calorimetric Determinations of the Heat and Products of Detonation for Explosives: October 1961 to April 1982", UCRL-52821 (April 5, 1982).

10. E. Lee, H. Hornig and J. Kury, "Adiabatic Expansion of High Explosive Detonation Products", UCRL-50422 (Lawrence Livermore Laboratory report; 1968).

11. B. Dobratz, "Properties of Chemical Explosives and Explosive Simulants", UCRL-51319, Rev. 1 (July 1974).

12. D. Ornellas, "The Heat and Products of Detonation of Cyclotetramethylenetetranitramine, 2,4,6-Trinitrotoluene and Bis[2,2-dinitro-2-fluoroethyl] formal", J. Phys. Chem., 72, pp. 2390-2394 (1968). Dr. Ornellas has informed me that the oxygen-balance definition is incorrectly stated in this paper (p.2390); it should read OB(%)=[d-21-.5(b-e)](1600/MW), where a,b,c,d,e are the numbers appearing in the molecular formula $C_aH_bN_cO_dF_e$.

COWBOY TRAILS, PHASE I: SMALL-SCALE EXPLOSIVE TESTS IN SALT DOMES
PART II - EXPERIMENTAL PROGRAM

by

Franklin C. Ford

SECTION 1

INTRODUCTION

The work described in this report was conducted as a subcontract effort in support of the ATI program to establish experimentally a relation between energy-release and cavity-volume increase for chemical explosives (CE's) tamped in dome-salt as a basis for later determination of the yield of Pelletol in tamped COWBOY events.[1,2] The experiments described were carried out by PAI in the United Salt Co. mine at Hockley, Texas, using both oxygen rich and oxygen deficient CE's. Since the salt mine had only one working level, at 450m, the effect of overburden on cavity-volume-increase could not be evaluated; however, recent work at LLL indicates that for any reasonable range of overburden pressures, the effect of overburden on cavity-volume-increase is essentially negligible.[3]

The salt medium available for performing tests consists of a massive crystalline salt dome intrusion into the earth's crust. Salt densities are slightly above crystalline density for pure NaCl due to the presence of some anhydrite ($CaSO_4$): H_2O.

The salt dome appears to offer an isotropic, homogeneous medium for testing. There is no evidence of layering, little or no moisture, no shale stringers, and no evidence of trapped gases. The salt dome is a cylinder roughly 1600m in radius and the dome top is located about 300m below the earth's surface. There is no recorded measurement of the dome depth below the working level but it is in excess of 300m.

The general procedures for the tests and the explosives to be used were reviewed and approved by ATI personnel. Test locations in the mine, at the 450m working level, were selected by PAI in cooperation with mine operator personnel. All tests were conducted in the tunnel floor in the same tunnel-drift area of the mine by PAI personnel. Logistic support was provided by United Salt Co. ATI as prime contractor, carried out analytical and theoretical support of the experiments.

The in-situ tests consisted of both oxygen rich (fixed energy) and oxygen deficient (variable energy) spheres of CE's in masses ranging from 20 to 30 grams. PETN was selected as the best of the available known fixed energy CE's while NM and TNT were selected as candidates for the variable energy CE's. Two densities of PETN, TNT and RDX were used in the tests. NM a liquid CE, was available at only one density ($1.13 g/cm^3$). RDX was selected as a moderately variable energy CE.

Section 2 of the report covers the details of the CE charges and the detonators.

Section 3 of the report covers Test Program Procedures including emplacement, arming and firing, reentry to the cavity and cavity measurement.

Section 4 of the report summarizes the results and possible sources of error.

Section 5 of the report covers conclusions and recommendations as they relate to the experimental techniques and measurements.

Section 6 lists references.

SECTION 2

HIGH EXPLOSIVES

The explosive charges used in these tests were fabricated by Brower Associates, Pomona, California to PAI specifications. A set of high and low density PETN, TNT, and RDX hemispheres 3.175cm dia. were pressed from the chemical explosive (CE) powders and, following emplacement of the detonators in the center of the charges, the hemispheres were glued with plastic model cement to form spherical charges. The CE's were stored in a magazine on the working level of the mine, underground, until used. PETN was selected as a known oxygen rich (fixed energy) explosive while TNT and NM were selected as a moderately variable energy CE. NM was sensitized with 3% EDA (Ethylene Diamine) prior to tests; all other CE's were used uncontaminated.

2.1 DESCRIPTION

Apart from NM, the CE's used in these tests were all fabricated from pure powdered materials. Densities of the powders ranged from $1.0 g/cm^3$ for TNT to $1.15 g/cm^3$ for PETN. Both PETN and TNT are white powders while RDX is a pale yellow color. None of these materials is cohesive at densities below $1.15 g/cm^3$. For ease of handling most of the low density charges were formed to densities which were cohesive masses. When formed, the materials were encapsulated in saran wrap plastic until detonated. NM is a colorless liquid of density $1.13 g/cm^3$ (STP). Without a sensitizing agent, NM is not considered an explosive by DOT although it can be detonated by heating under confinement or by severe/rapid compression under adiabatic conditions. NM can be sensitized with most amines up to a point where detonation can occur even under mild impacts, but for these tests only the standard 3% EDA sensitizer was used so that the material could be safely handled and detonation would require at least a No. 8 blasting cap. NM is a chemical solvent but can be stored or contained without contamination in containers of teflon, polyethylene, polypropylene, glass, and nitrile rubbers.

(In these experiments the NM liquid was put into cavities that had been milled into the salt and coated with a plastic spray paint (flectoverithane).

2.2 DETONATORS

In all cases the detonator used was Reynolds' Industries' RP87. The RP87 is a miniature exploding bridge wire detonator (EBW) whose 0.1g PETN charge creates the shock pressures required for initiation of detonation in CE's. The EBWs were attached directly to the solid explosives. Generally, an EBW was glued to a small depression in the center of a given CE hemisphere; a small cut in the flat surface of the hemisphere permitted the EBW leads to exit from the CE without leaving a gap, when two hemispheres were assembled to form a complete spherical CE charge. However, in one PETN test, powdered material was assembled without gluing the EBW, by pouring the CE powder over the centrally located EBW. The EBW lead wires were glued to the salt core to prevent any change of EBW position while fabricating and emplacing the core-CE assembly. The EBWs were fired with a portable battery charged EBW set, Reynolds' Industries' Model FS3C, which provided a pulsed high voltage, high current supply of 3KV and 2,000 amperes. Pulse duration was about 1 μsec, which provided about 20 times the energy required in the EBW for satisfactory initiation of the 0.1g PETN detonator charge of the RP87. The firing cable was 15m of RG-58u fitted with standard amphenol connectors at the EBW firing box end and a pair of leads with alligator clips at the EBW end for ease of connection to the EBW leads.

SECTION 3

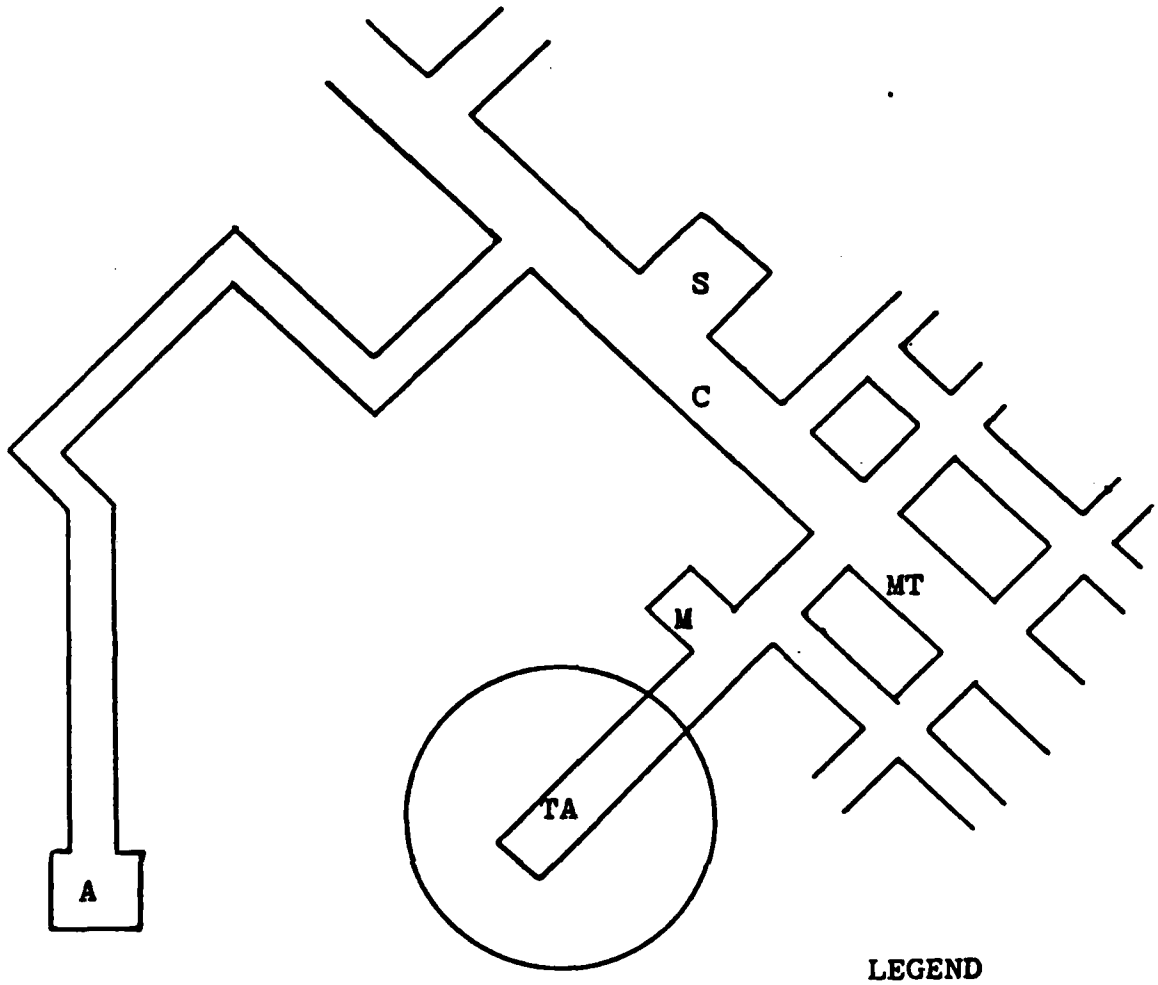
TEST PROGRAM PROCEDURES

Figure 1 shows the location of the tests in the United Salt Co. Hockley Mine. The mine working area is approximately 450m below the ground surface. Figure 2 is another view of the work area. Figure 3 is a cross-section of the Hockley Dome showing the stratigraphy. The working tunnels are about 15m wide and 6m high. The PAI site was about 45m from the end of the drift. The floor of the tunnel was found to be in excellent condition since it was protected from mine blasting effects by the manner in which the salt was mined in this area; i.e., the tunnel face was undercut by a saw-type tool to a depth of 5m from the face along the floor in such a way that a blast and block-caving technique could be used to bring down the tunnel face for mucking. The saw cut inhibited the transfer of strong shocks into the tunnel floor. All tests were carried out in the tunnel floor at a depth of about 35cm and a spacing of 2 meters. After charge emplacement, the grout was allowed to set for a minimum of 48 hours. To prevent minor surface spall, several bags of salt were placed on top of the shot site prior to firing.

3.1 EMPLACEMENT OF C.E.

The dry, solid CEs were emplaced as follows: A core about 45cm long was removed from the mine floor using a 15.24cm core drill lubricated by saturated brine water. The brine water held the radial gap between the central core and the outer wall of the core-hole to less than 0.3cm. Typical coring time was 5 minutes after set-up. The core was fractured in place by wedging it to one side of the core hole with a pinch-bar type tool. It was removed by drilling a 0.635cm hole to a depth of 1.905cm in the center (top) of the core and forcing a wooden dowel into the 0.635cm hole to form a lifting handle.

To section a core, a chisel cut was made at an appropriate point above the lower end of the core, keeping the lower section



LEGEND

A - Mine Shaft
S - Shop
C - Crusher
MT - Main Tunnel
M - Magazine
TA - Test Area

Fig. II-1 Location of Test Area in the United Salt Co. Hockley Mine (schematic)

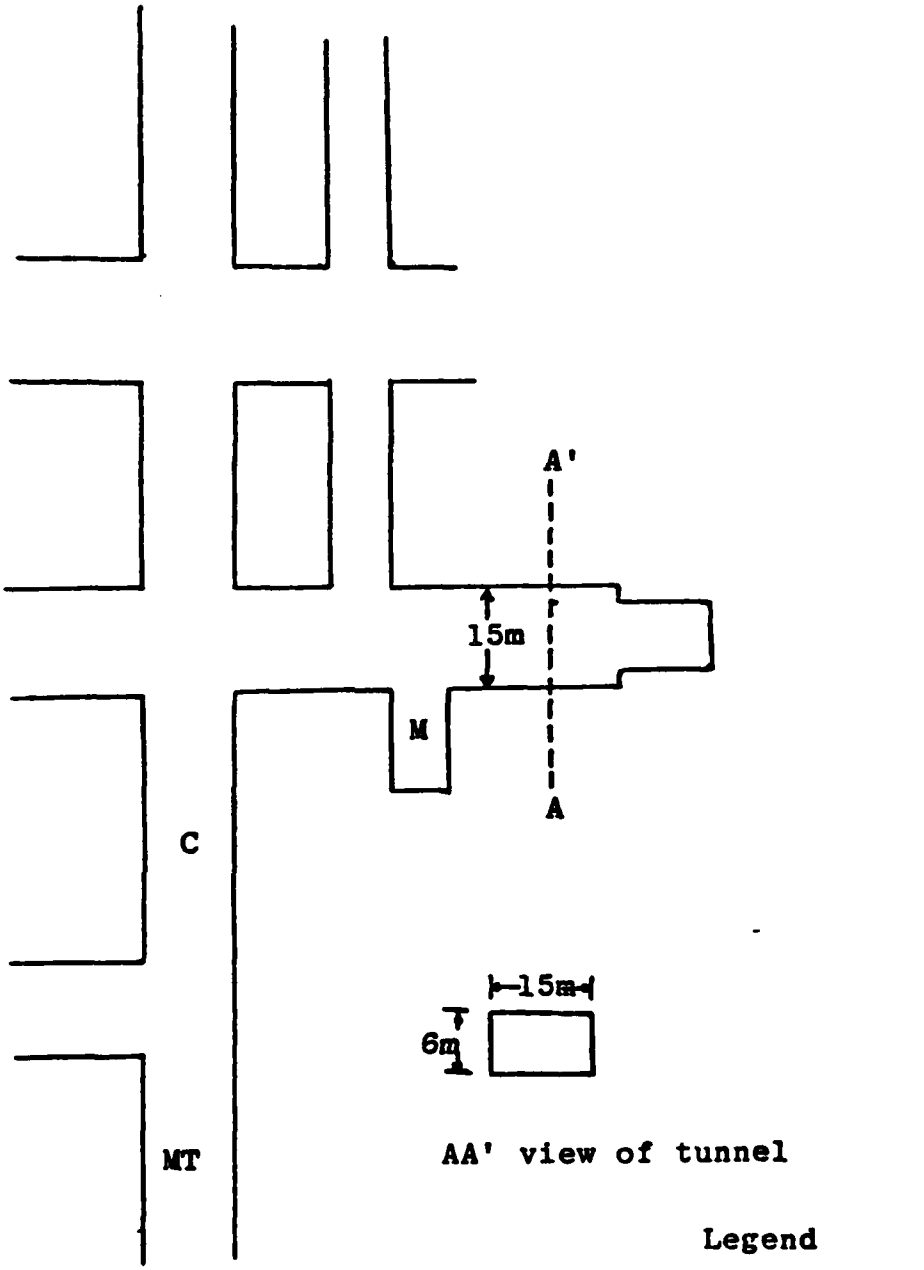


Fig. II-2 PAI Work Area USC Hockley Mine

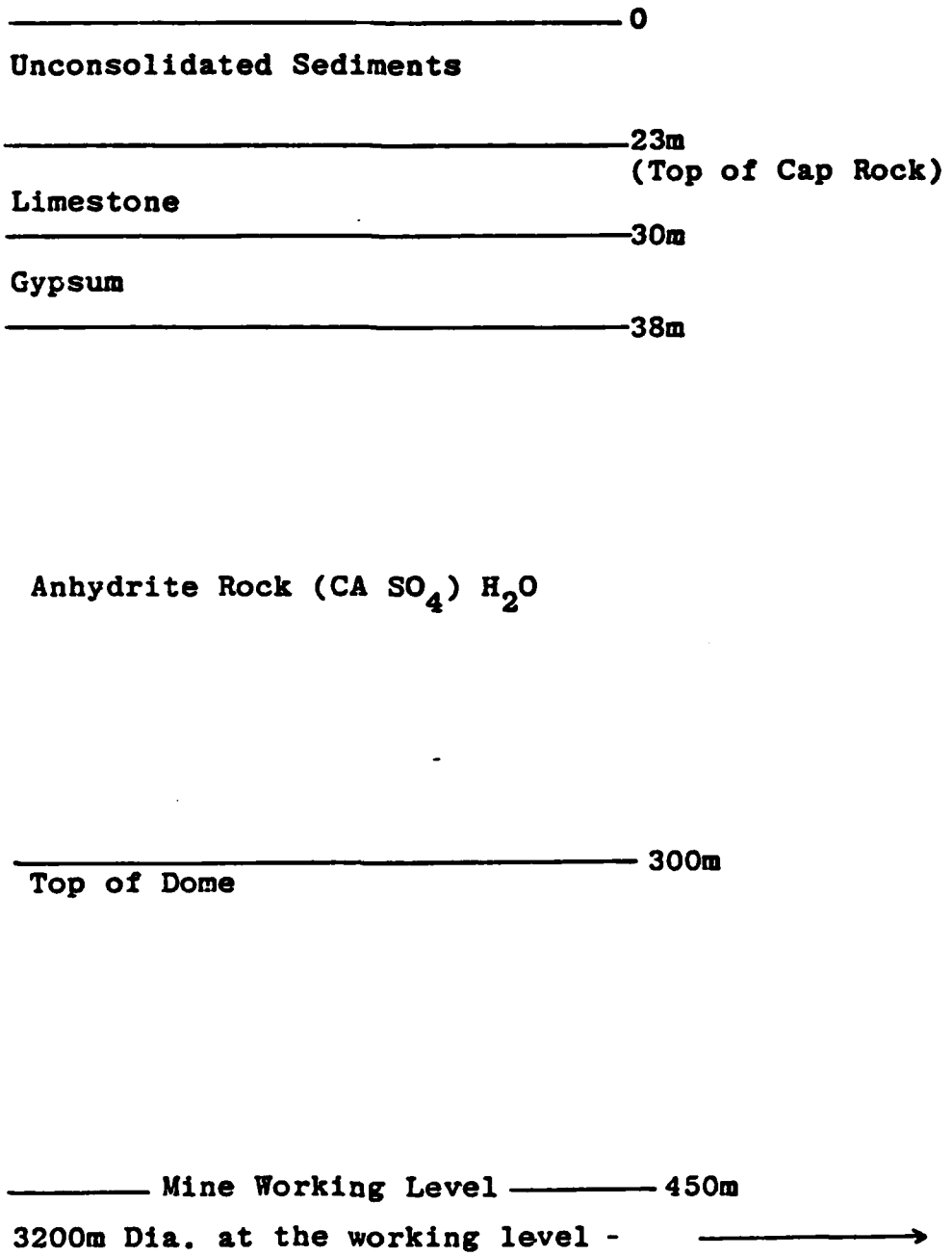


Fig. II-3 STRATIGRAPHY OF HOCKLEY DOME

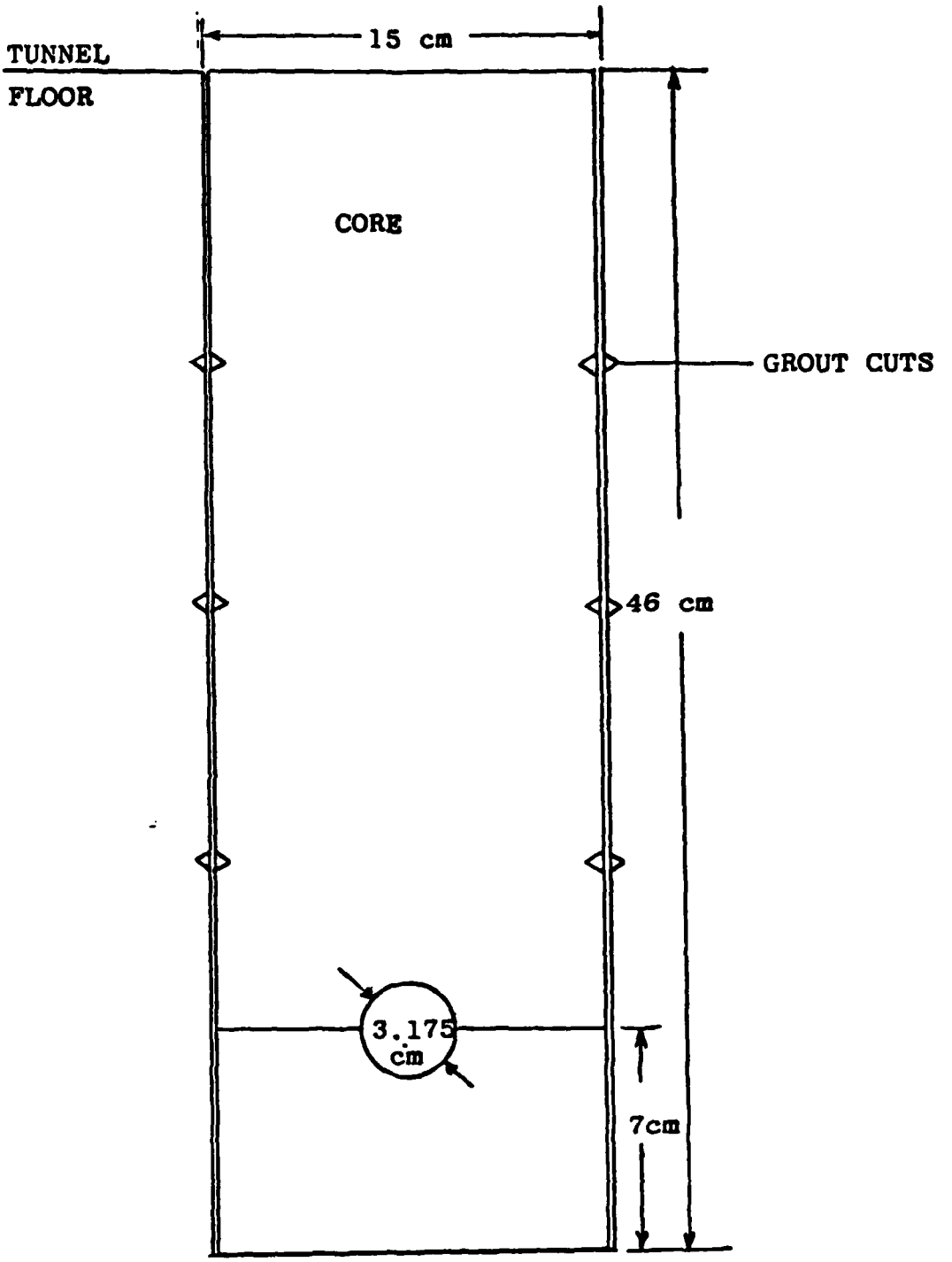


Fig. II-4 EMPLACEMENT DETAIL

at least 7cm thick; Figure 4 shows the core-cut details. The core was marked with vertical lines so that it could be reassembled in its original orientation after loading it with CE. CE was placed in two hemispherical holes that were machined into the central area of the core by a standard 4 flute 3.175cm ball reamer. To accomodate the detonator leads, a saw blade cut was made radially from the rim of the hemispherical holes to the outer edge of the core. With the explosive placed in the reamed holes so as to form a spherical charge, the core was reassembled without gluing to determine whether appropriate clearances were available. If either additional reaming or trimming of the core face was required to seat the CE properly, it was accomplished by disassembling the core and using a wood rasp/hack saw or ball reamer.

At this point, drilling water in the hole left by core removal was siphoned out. The remaining moisture in the core hole and on the core itself was removed by drying with warm air from a hair dryer. The side walls of the core hole and core were notched to provide a stronger grouting configuration (see Fig. 4). Epoxy grout was prepared using a two-component anchor bolt grout of the resin-curing type. The grout was previously tested in the laboratory and was found to have exceptional strength, negligible shrinkage, superior adhesion to salt, and cured in the presence of moisture. About $10cm^3$ of grout was poured into the hole. A final assembly of the detonator, explosive and core was prepared using plastic model cement to attach the EBW to the charge; epoxy grout was used to glue the salt-core pieces together, and the core was then ready to be placed back in the hole left by its removal. To assure that the cylindrical core remained intact during emplacement, it was held together with a wire-tie traversing a vertical path around the core. The EBW leads were brought to the surface alongside the core as it was gently lowered into the hole and grouted. The core was oriented to its original position, grout was added in an amount sufficient to fill the space between the core and mine-salt from which it was cut.

Since NM is a liquid, a somewhat different process had to be developed for its emplacement. After chiseling the core into two

pieces and reaming hemispherical holes into each, a coating of plastic (flectoverithane) was sprayed on the core to prevent contamination of the NM by salt and/or penetration of NM into the salt. The core was reassembled, as before, using epoxy glue and a flexible plastic putty to seal the interface, and a tie-wire to hold the assembly together. A 0.635cm hole was then drilled from the core circumference to the cavity along the glued fracture joint. An EBW was inserted through the 0.635cm hole to a previously determined depth so as to be centrally located in the cavity. NM was poured into the 0.635cm hole, through a small plastic straw and funnel until the cavity was full. The quantity of NM used was recorded. After 24 hours the NM level in the cavity was checked for evidence of leakage. If there was no change of liquid level, standard mortar grout was prepared and allowed to set up to the point where it could be formed into a small ball. That ball, along with a small rubber grommet, was forced into the 0.635cm hole along the EBW leads until it reached the edge of the cavity. A small quantity of epoxy grout was then poured into the hole and allowed to harden, after which the hole was completely filled with mortar and epoxy grout.

The CE powders (PETN and TNT at low densities) were emplaced as follows: a core was removed, cut in two and the hemispherical cavities machined as for NM. The EBW was centered in the lower cavity hemisphere and the EBW leads were glued to the salt core in their radial slot. CE powder was added from a measured quantity until the hemisphere was filled. A circle of epoxy grout was then laid on the face of the core-cut at a small distance from the rim of the hemisphere. A layer of saran wrap, 1/2 mill thick, was then glued to the circle of epoxy grout so as to hold the powder in place. The upper cavity was treated in a similar way and the quantity of CE powder used was recorded. When the epoxy holding the saran wrap had set, the radial slot for the EBW leads was filled with a standard mortar and the core reassembled by gluing with epoxy. A wire-tie was used for reinforcement and stability of the reassembled core.

After all cores were loaded, returned to their proper core hole locations, and grouted into the floor of the tunnel, a period of 48

hours was allowed for the grout to reach maximum strength. During this period, cores were cut from the tunnel floor in the test area for shipment to Terra Tek, Salt Lake City, for laboratory examination and test. 6 cores were cut in the same manner as the replaceable cores used for the tests.

3.2 ARMING AND FIRING

The portable, battery charged, EBW firing unit was a Reynolds' Industries' Model FS3C. When not in use the unit could be recharged from any conventional 110V source. The unit has a built-in safety feature in the form of a toggle switch which must be held continuously in the closed position while charging and firing the unit. If the toggle switch is allowed to return to its neutral position, the firing box is automatically crow-barred (shorted). The EBW leads were connected to the RG-58u firing cable which was equipped with alligator clips to facilitate rapid hook-up. 15m of cable was then extended away from the shot point and attached to the firing box. About 30 seconds were required to charge and fire the shot. There was no requirement for an accurate firing time fiduciary so the charges were fired when the EBW firing unit showed full charge. After firing, the cable was disconnected from the firing box and from the EBW leads. This process was repeated for all the emplaced charges before any of the holes were reentered. At 15m from the charge, the detonation was clearly audible and some surface spall of loose material (salt, extra grout, etc.) was seen to occur. No venting or throwout from the shot was evident. Visible damage from the shot was limited to a few hair-line fractures at the surface of the epoxy grout.

3.3 REENTRY

The mine floor around the tops of the cores was examined for spall, fracture, etc. No venting occurred during the tests, even when hair-line fractures developed in the epoxy grout. There was no evidence of loose surface material in any of the tests performed. The grout completely and effectively stemmed and contained the shots.

The 10cm core drill was set up and centered over the 15.24cm core at the shot point. Using saturated brine as a drilling fluid once again, the 10cm core was drilled to a depth of 23cm to 25cm

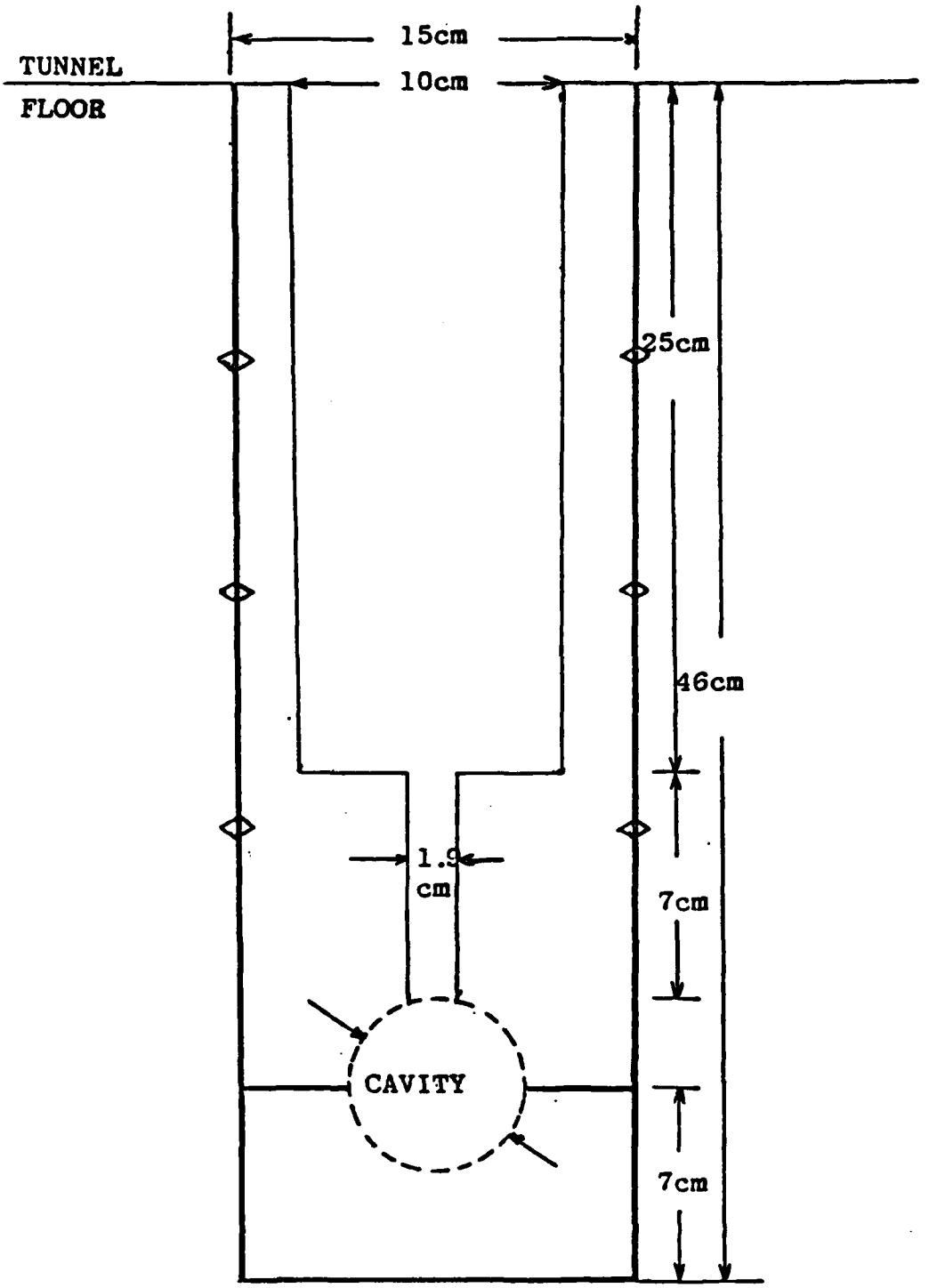


Fig II-5 REENTRY DETAIL

and the core removed. Brine water in the 10cm core hole was then siphoned off and the core and core hole walls were examined for cracking, etc. About 3.8cm from the top of the 10cm core, a clearly visible fracture plane parallel to the surface was present.. The core hole showed the same fracture plane and a core sample approximately 30cm from the shot point also revealed a fine-line fracture. There was no obvious communication between shot points, i.e., drilling fluid did not reach the other shot points as determined by drilling 1.905cm holes at 30cm intervals along the shortest surface paths between shots.

The 10cm core hole was cleared of salt debris and a pulsed air surge was used to lift any remaining water/debris out of the hole. A 1.905cm diameter rotary-impulse drill, Hilti Type 52, was used to drill the remaining distance to the cavity. No water/brine was used in this part of the operation and the drill was removed frequently to allow the drilling rubble to be cleared from the hole. Once cavity penetration occurred the drill was removed and air jets were used to blow as much loose debris from the cavity as possible. At this point, cavity measurements were made to determine the new volume. After cavity measurement, the coring was continued in an attempt to retrieve an intact cavity. In every case, the cavity fractures resulted in cave-in or collapse; no cavity could be recovered free of damage from coring and/or attempts to remove the core from the hole. Overcoring with a larger core drill has been recommended by ATI and will be tried in an attempt to recover a shot cavity intact for closer examination.

3.4 CAVITY MEASUREMENTS (TECHNIQUES)

During the COWBOY series a cavity measurement technique was developed using sand.[2] The same technique was used in these experiments. The procedure for cavity measurement after reentry was as follows: Air jets were used to blow as much of the loose debris out of the top of the cavity as possible. A steel tape was lowered into the cavity to record the depths of its top and bottom. These measurements proved to be difficult for such small cavities due to the irregular fracture patterns produced by the reentry drill at the top of the cavity. Some moisture, probably due to brine water

used during reentry drilling and coring, was observed in a few of the holes after reentry and the air jet/siphon was used to dry the cavities prior to volume measurement with the sand. The sand was pre-measured in a graduated cylinder by first filling the cylinder from the sand source and then alternately pouring the sand from the cylinder into a beaker and back into the cylinder. Depending on how the repour was made, the sand volume varied by ± 3%; i.e. slight tapping of the cylinder to level the top of the sand for measurement would reduce the apparent volume while rapid pour with no tapping would result in an apparent increase of volume. Moving the sand to level the top with a small air blast or a screw driver resulted in fairly reproducible sand-volume measurements. After several trials, a rate of sand pour was selected that gave reproducible results (± 2%) particularly when the surface level of the sand was established by gently moving the top layer of sand with a screw driver. Sand was then poured into the cavity from the graduate through a small funnel. From the steel tape measurements, the approximate volume of a spherical cavity was estimated and this permitted most of the sand to be poured, in a single pour, into the cavity without fear of overflow. When the sand level approached the top of the cavity at the reentry hole, the air jet was used to gently move the sand away from the pile-up in the center. When the sand level reached the top of the cavity, at the reentry hole, a small screw driver was used to move the sand away so as to fill the cavity as completely as possible. Usually, about 10-15cc of sand could be added to the cavity before the cavity appeared to be full. Total sand poured into each cavity was recorded as the difference in the original quantity of sand in the graduate and the sand remaining after cavity fill-up. For several of the cavities, an attempt was made to recover the sand in the cavity by using an air bulb siphon. The recovery of some powdered salt and the incomplete recovery of sand produced major sources of error for this technique and it was not used in later tests. Only the volume of sand required to fill the cavity during an initial pour was used as a measure of cavity volume. An attempt was made to determine the effect of water in the cavity on the volume measurement. Fifty cc of sand was poured

into a graduate containing 50cc of water. The sand volume appeared to be about 47cc and the total water plus sand volume was 81cc. This procedure was repeated with relatively smaller quantities of water and large quantities of sand with the result that the observed "error" in sand volume was established to be less than 3% for the worst possible case of moisture in actual cavity measurements.

SECTION 4

RESULTS

Table I gives a summary of the experimental data for all 16 tests. In each case the type, weight and density of explosive, is listed along with the initial and final cavity volumes. For all CE's except NM, the weight of CE is known accurately and its density is derived from the measured weight and volume of the charge. Although the salt could be machined to a high tolerance (i.e. ± 0.013cm), core assembly led to some error in initial volume. Estimates of this initial volume error range from 0.5cm^3 to 1.0cm^3. In the case of NM, the density was well known and the weight of explosive used to fill the cavity was established by measuring the volume of NM used to fill the initial cavity. The volume so measured agrees with the machined initial volume corrected for the estimated initial volume error.

4.1 SOURCES OF ERRORS

The listed, known sources of error with appropriate discussion of ranges are given below.

1. CE WEIGHTS

   CE weights are accurate to ± 0.1% for all explosives tested with the possible exception of NM. In the case of NM, the potential error is the error in the measurement of the volume of liquid and is estimated to be of order ± 3% (maximum).

2. INITIAL VOLUME MEASUREMENT

   The two hemispherical volumes machined into the salt core are quite accurate (better than 0.013cm, or less than ± 0.4%) but the error in initial volume due to reassembly of the core as indicated by the NM required to fill the cavity ranges from +0.5cm^3 to 1.0cm^3 or a maximum of +6%. Since no other independent volume measurement was made, the "error" associated with the NM measurement is assumed

TABLE I

SUMMARY OF EXPERIMENT DATA

The data summary covers both high density CE tests and low density CE tests for all CE's except NM. The parameters listed were rechecked for each test at the time of test to eliminate any errors resulting from measurements made during fabrication of charges such as densities, and dimensions of all fabricated CE's.

Shot #	CE Type	CE Wt.	CE Density	Initial Vol	Final Vol	Remarks
1	TNT Pressed	26.4g	1.57g/cm^3	16.75cm^3	112cm^3	Hairline cracks in surface of grout
2	TNT Pressed	27.0g	1.57	"	117	OK
3	TNT Pressed	26.5g	1.57	"	115	Some moisture in hole. Dried out
4	TNT Pressed	20.0g	1.19	"	74	Some rubble in hole due to 3/4" drill
5	TNT Pressed	20.5g	1.19	"	79	OK
6	TNT Pressed	20.3g	1.19	"	50	Reentry hole at edge of cavity
7	PETN Pressed	27.0g	1.61	"	183	OK
8	PETN Pressed	28.0g	1.61	"	178	OK
9	PETN Pressed	27.1g	1.61	"	181	OK
10	PETN Powder	19.4g	1.15	"	124	Some rubble in hole
11	PETN Powder	18.5g	1.10	"	128	OK
12	PETN Powder	19.1g	1.14	"	129	OK
13	NM Liquid	19.5g	1.13	"	91	Water in cavity dried out
14	NM Liquid	20.9g	1.13	"	98	Some rubble in hole
15	RDX Pressed	28.5g	1.70	"	171	Some water in cavity Dried out
16	RDX Pressed	20.5g	1.21	"	125	H.E. Crumbled before emplacement

to be present (or possible) for all initial volumes.

3. RUBBLE AND SALT DEBRIS

Although the cavities appeared to be reasonably free of rubble, some rubble was present in the cavity, apparently as a result of reentry drilling. This rubble, while not removed from the cavity, did not create large errors in the measured final volume. The error introduced by such reentry rubble can be estimated by assuming that all of the material for the last 1.27cm of drilling from the 1.905cm diameter reentry drill hole - roughly 4cc of rubble - entered the cavity. Based on the results of Table I, this amount of rubble gives an error ranging from about 5% for the smallest cavity to 2.5% for the largest cavity. The magnitude of the error is assumed roughly constant at about 4cc and would reduce the measured volume from the true cavity volume by this amount. There is, however, the possibility that the top of the cavity is slightly enlarged when the debris falls into the cavity and this factor would reduce the error due to rubble.

4. SAND MEASUREMENT TECHNIQUE

As discussed in the text under, Section 3.4, CAVITY MEASUREMENT TECHNIQUES, the sand-fill method of cavity volume measurement presents several sources of error; i.e. pile-up of the sand may prevent filling of the total void space, fluff-up (or compaction) of the sand volume due to trapped air (or compaction due to tapping or vibration of the sand), effects of water on sand volume, effects of cavity rubble, etc. Due to efforts made to avoid fluff-up or compaction, this error appears to be small (less than ± 2%). The error due to incomplete filling of the cavity is not known, but attempts to move the sand away from the fill-hole appeared to result in a complete filling of the cavity. Correction could be made for the drilling rubble so that the overall cavity measurement error due to the sand technique is probably less than ± 5%.

5. VOLUME OCCUPIED BY DETONATOR (EBW)

The initial volume of 16.75cm^3 listed in Table I includes the volume available for the explosive and the EBW. A small correction in volume could perhaps be made for the EBW although the 1/4cc volume of the EBW includes about 0.1g of PETN so that the volume error is quite small (i.e. less than 0.15cm^3) and is estimated to be less than 1%.

SECTION 5

CONCLUSIONS & RECOMMENDATIONS

The following recommendations are based on the results obtained for the 30-gram tests discussed in this report:

(1) A cavity resulting from the tests should be carefully recovered and the cavity volume remeasured for comparison with cavity volume measurement by the sand technique listed in Table I. Actual cavity recovery will permit a) measurement of the sand volume contained b) measurement of the cavity by use of either a finer powder or a viscous liquid and c) a visual examination of the cavity shape, cracks, irregularities, rubble sources, etc.

(2) The cavity volumes should be measured using the finest available quartz (or silicate) sand. That will eliminate as far as possible errors due to irregular sand grains, large sand grains, etc.

(3) In reentering the cavity no fluids should be used for drilling or coring.

(4) In future experiments of this type, explosives should be emplaced so as to permit measurement of the effects of overburden.

APPENDIX IIA

PHASE I EXPERIMENTS AT GRAND SALINE

1. Scope of Effort; Charge Emplacement and Cavity Measurement

Two PETN and two NM explosive events were carried out in the Morton Mine at Grand Saline, Texas. The events were similar to the small charge tests carried out at the Hockley mine as part of the Phase I effort. The charge weights were roughly 2.5 times the charge weight used in the Hockley tests and the salt cores for the charge emplacement were 8" in diameter rather than 6" as in the Hockley work. The charges were placed in cavities located in eight inch diameter salt cores and the cores were grouted into holes drilled in the floor of the mine. Preparation of the salt cores and emplacement were accomplished as follows:

Four eight-inch diameter holes were drilled into the mine floor at a minimum spacing of 6 feet. Two eight-inch salt cores were cut from the nearby mine floor area for later assembly and emplacement in each of the eight inch holes. Eight such cores were taken plus two spares. For each explosive test, two cores were carefully faced off in a lathe to provide faces perpendicular to the cylindrical axis of the cores. Each core was centered in the lathe and a two inch diameter hemispherical hole was machined in one end of each core. One of the cores (selected to be the top core in the hole at assembly) was drilled on axis from the hemispherical hole to the other end to provide for detonator emplacement during final assembly.

For the PETN tests, a measured amount of PETN powder was placed in the bottom core to fill the hemispherical hole. Similarly, a detonator (inserted through the 5/8" hole) with a small stemming plug at the top of the hemispherical cavity and an additional measured quantity of PETN powder were added to fill

the hemispherical hole in this top core. The two salt cores were then coated with a thin layer of epoxy around the PETN powder, a thin mylar sheet was placed over each hemispherical charge, and the two cores were assembled to form a closed spherical charge and cavity. The two cores were then held in the assembled position by a nylon line surrounding the cores in an axial direction. This nylon line served as a handle to lower the cores into the eight inch drill holes. Fig 1 shows the core assembly detail.

For the NM shots, the hemispherical surfaces of the cores were treated with a thin epoxy coating to seal the surfaces. The cores were then glued together with Brutum 33 epoxy and allowed to set until the epoxy glue hardened. NM was then poured into the spherical cavity inside the cores through the 5/8" hole. A detonator was inserted to depth in the cavity and a stemming plug was pushed to the top of the cavity as for the PETN shots. The assembled and loaded core was tied with nylon cord to prevent axial separation during emplacement into the 8" drill hole and to provide a handle for core emplacement into the 8" hole.

All shots were grouted in place by putting two quarts of Brutum 75 epoxy in the bottom of the 8" hole and lowering an assembled and loaded core into place. Additional Brutum 75 was poured over the core to fill the 5/8" dia hole and cover the core to a depth of at least 2" with epoxy. The epoxy was allowed to set overnight for a period of at least 18 hours.

The first shot was PETN. In addition to the grouting, it was stemmed with powdered salt to the mine floor and a 60# bag of powdered salt was added above the hole. This shot spalled such that the top part of the core came out of the hole. Separation of the cavity occured at the glue joint at the mid-plane of the two hemispherical cavities. The bottom part of the core

was intact and still locked in place in the eight inch hole. Portions of the core face still had the Brutum 33 glue in place. The cavity formed in the bottom part of the core by the explosives was perfectly formed and undamaged. The cavity measurement for this shot consisted of carefully measuring this 1/2 cavity and then simply multiplying the result by 2 to determine the cavity volume. Later, a second NM test would indicate that this technique would underestimate the "true" cavity volume created by the charges by about 50 cc due to a separation of the two hemispherical cavities at the glue joint of the cores equal to 50 cc.

The remaining shots were stemmed to the mine floor surface with dry, powdered salt. A two foot sq piece of 3/4" thick plywood was placed over the stemmed hole with an additional 100 lbs of salt in a plastic canister placed on top of the plywood cover over the hole. These shots were completely contained although later examination showed the separation occuring at the glue joint mentioned above.

A standard x-unit firing box was used to detonate the CE for all shots. Reentry to the cavities in these contained shots was made by removing all loose, powdered salt to the top of the epoxy grouting and drilling back into the cavity with the 5/8" drill. A flexible plastic tube was inserted into the cavity and all small debris was removed from the cavity by vacuum. The bottom to top dimension of the cavity was determined by using a standard measuring tape. Powdered salt was then added to the cavity from a graduate to measure the cavity volume. Care was taken to make sure the powdered salt was not allowed to cone-up in the cavity by using small bursts of air to move the salt around in the cavity. Additionally, the 5/8" holes were

enlarged to 1½" and the cavity measurements were repeated. Finally, an attempt was made to core the region around the cavity to permit actual examination of the cavity. One of the cavities was destroyed using this technique. The two remaining intact cavities were then filled with epoxy through the reentry hole and, after the epoxy had hardened, were recovered intact.

2. Summary of Data and Results Obtained:

Initial Cavity Volume, all tests (2" dia sphere) --- 68.6 cc

Test No. 1 (Top core expelled from hole during test, bottom core intact)

PETN EXPLOSIVE	62 grams
V_o	68.6 cc
V_f(2 x hemispherical vol)	368 cc

NOTE: Only ½ of final cavity volume could be measured. See text.

The hemispherical volume of the bottom core was carefully measured using ruler and calipers and, as in the case of the Phase I shots at Hockley, this volume was measured again using the sand fill technique.

The cavity diameter was	3.5"
The cavity depth was	1.7"
The sand volume was	183 cc

Test No. 2 (Contained)

PETN EXPLOSIVE	75 grams
V_o	68.6 cc
V final (measured by sand fill)	510 cc
ΔV (calculated)	441 cc

$\frac{\Delta V}{m}$	5.9 cc/g

Height of cavity (vertical line) 4.0"

NOTE: Based on the vertical height dimension, and assuming a spherical cavity, the final volume would be about 550 cc and the volume increase about 480 cc.

Test No. 3 (Contained)

NM EXPLOSIVE	77 grams
V_o	68.6 cc
V_f (measured by sand fill)	412 cc
ΔV	343.4 cc
$\frac{\Delta V}{m}$	4.6 cc/g
Δh (vertical cavity dimension)	3.75 inches

Test No. 4 (Contained)

NM EXPLOSIVE	77 grams
V_o	68.6 cc
V_f (measured by sand fill)	395 cc
ΔV	326.4 cc
$\frac{\Delta V}{m}$	4.24
Δh (cavity height)	3.75 inches

The volume measurements above are subject to the following possible error apart from the errors discussed in the Phase I report:

When the cavities were cast with epoxy and recovered, examination showed that all contained tests separated at the mid-cavity glue joint by approximately 0.5" in the center of the

cavity tapering to zero at 2.5" radius from the cavity center. An estimate of volume outside the cavity radius to a point about 3/4" further out in radius where the separation appeared to cease was obtained by calculations and determined to be about 13 cc. Figure 2 shows the dimensions of this separation region as determined from the epoxy casting. During sand fill to measure the cavity volume, this region may not have been completely filled with sand. The maximum error due to this factor is estimated to be about 12 cc which reduces to about 3 percent to be added to the volume increases observed.

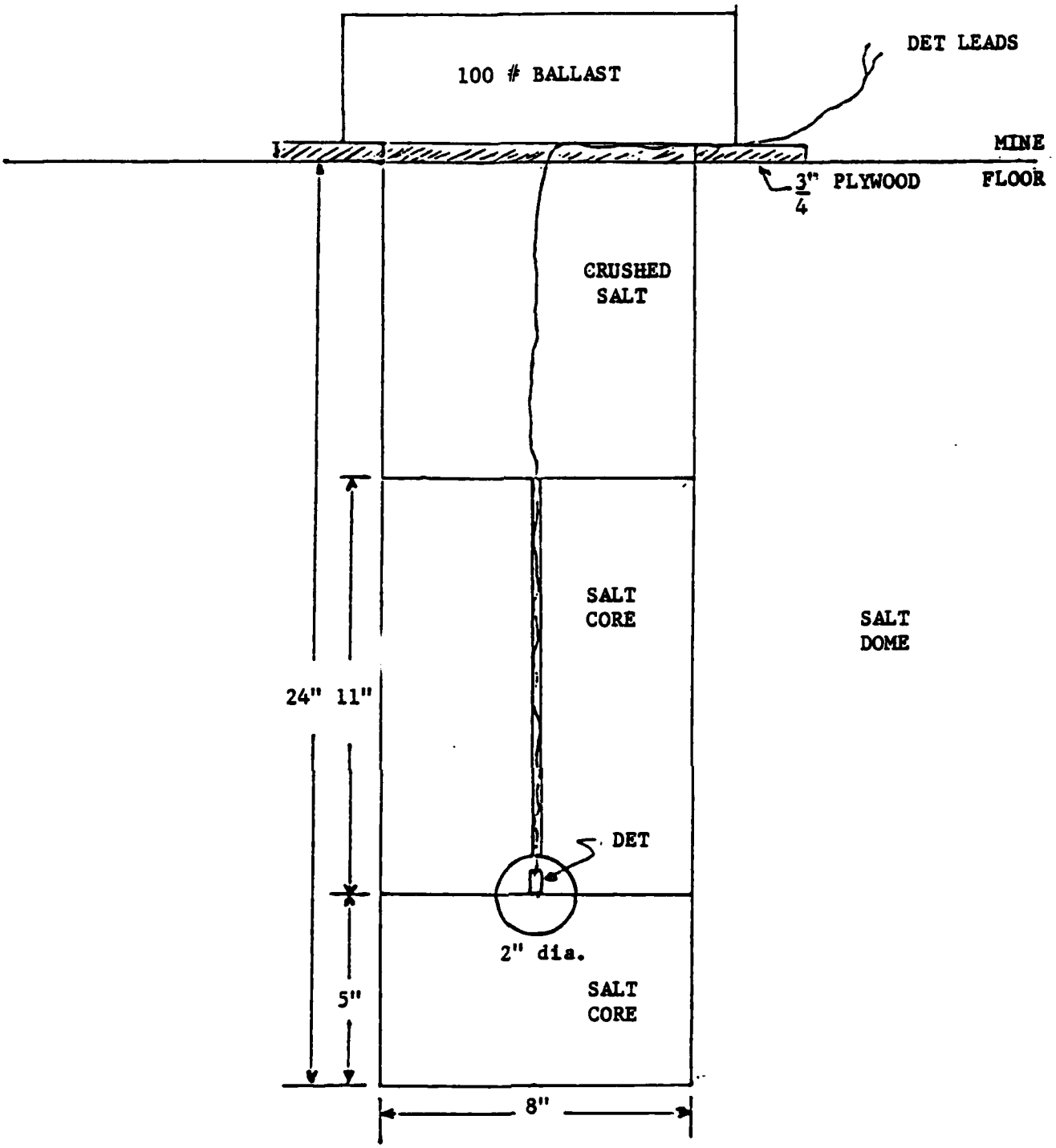


FIG 1

Emplacement Detail

An 8" hole was drilled into the mine floor. A 5" and 11" core were machined and assembled to form a 2" diameter cavity as shown. A 5/8" hole drilled in the 11" core permitted assembly and loading of the cavity with CE and a det. Crushed salt and ballast were added after grouting to help contain the shot.

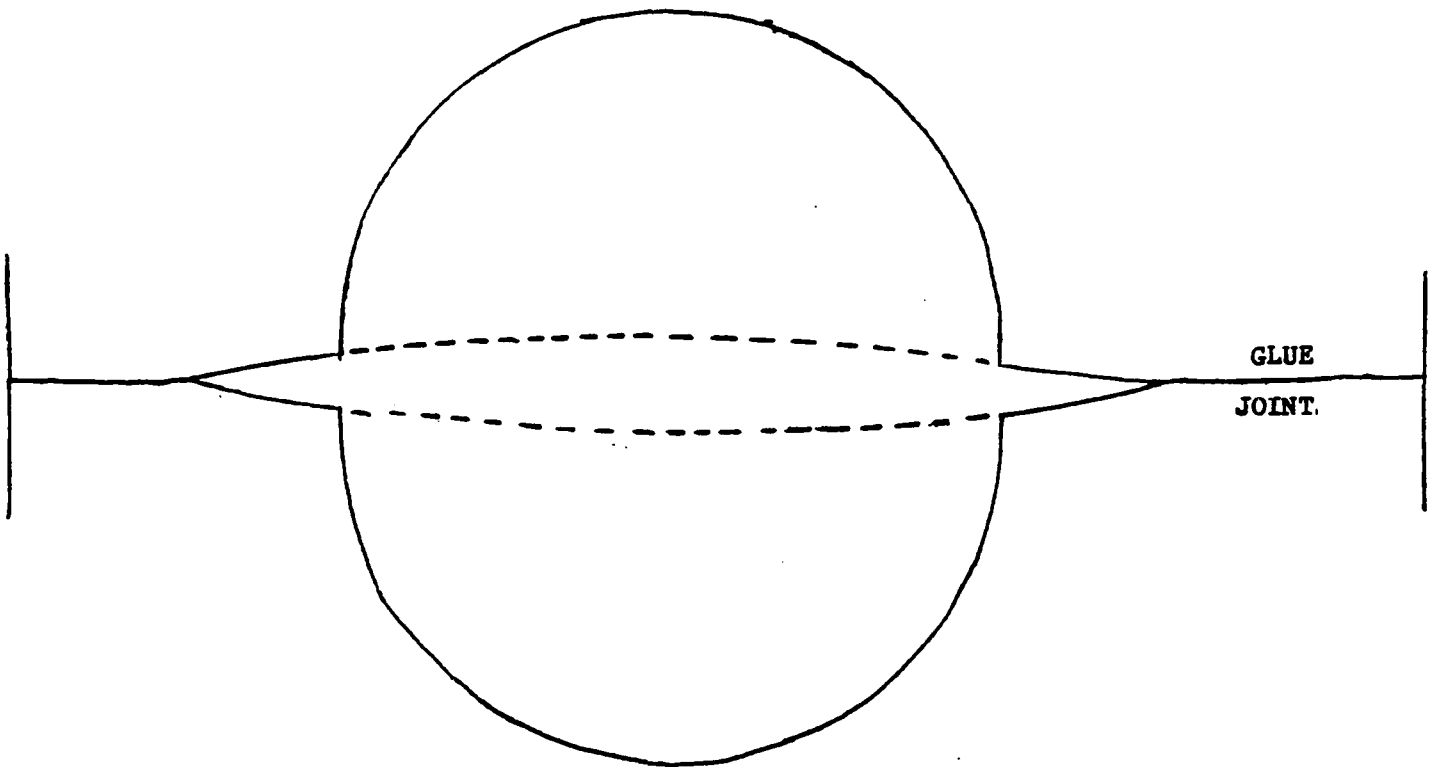


FIG 2

POST-EVENT CAVITY SHAPE

Cross Section of Post-Event

Cavity showing separation at glue joint extending approximately 3/4" beyond cavity radius. Maximum separation at the center is 0.5" tapering to zero at a radius of 2.5". The dotted lines interior to the cavity are intended to show the volume added by separation of the cavity at the glue joint.

SECTION 6

REFERENCES

1. J. Trulio, "Energy Released in Tamped COWBOY Events", ATP-281, Feb 1979.

2. W.A. Hamilton, L.Ballou, C.Benedix, R.Petrie, "Permanent Displacements", UCRL 6282

3. D. Larson, Private Communication